Economic and Policy Implications of Environmental issues

Marion Davin

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RAPPORT DE SYNTHÈSE
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Economic and Policy Implications of Environmental issues

Marion Davin

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Tuteur de l'HDR: Fabien Prieur, Professeur à l'Université de Montpellier

Je déclare avoir respecté, dans la conception et la rédaction de ce mémoire d'HDR, les valeurs et principes d'intégrité scientifique destinés à garantir le caractère honnête et scientifiquement rigoureux de tout travail de recherche, visés à l'article L.211-2 du Code de la recherche et énoncés par la Charte nationale de déontologie des métiers de la recherche et la Charte d'intégrité scientifique de l'Université de Montpellier. Je m'engage à les promouvoir dans le cadre de mes activités futures d'encadrement de recherche.

LIST OF PAPERS PUBLISHED PRESENTED IN THE THESIS

(In order of presentation)

- The Role of Health at Birth and Parental Investment in Early Child Development. Evidence from the French ELFE Cohort, with E.Lavaine. European Journal of Health Economics, 2021.
- Pollution, children's health and the evolution of human capital inequality with K.Constant. Mathematical Social Sciences, 2021.
- Environment, public debt and epidemics, with M.Fohda and T.Seegmuller. Journal of Public Economic Theory, 2022.
- Unequal vulnerability to climate change and the transmission of adverse effects through international trade, with K.Constant. Environmental and Resources Economics, 2019.
- Pollution in a globalized world: Are debt transfers among countries a solution?, with M.Fohda and T.Seegmuller. International Journal of Economic Theory, 2022.

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1. FRENCH SUMMARY

Dans ce résumé en français, je présente synthétiquement mon expérience de recherche au sein du centre d'Économie de l'environnement de Montpellier (CEE-M), le laboratoire dont je fais partie depuis 2015.

1.1. *Présentation générale*

Ma recherche se focalise sur les interactions entre environnement et économie et leurs implications en termes de politiques économiques et de croissance. J'ai une approche principalement théorique, basée sur des modélisations macroéconomiques dynamiques qui m'ont permises d' examiner les relations de court et de long terme entre pollution et inégalités d'une part et entre économie internationale et problèmes climatiques d'autre part. Dans une perspective de long terme, il est important de comprendre comment une économie améliore sa résilience aux changements environnementaux et peut atteindre une croissance durable compatible avec les objectifs environnementaux. Ma recherche vise ainsi à examiner les politiques publiques pouvant être utilisées comme moteurs potentiels d'une transition vers une économie durable. Depuis ma nomination à l'université de Montpellier comme maîtresse de conférences en 2015, j'ai intégré dans mes problématiques de recherche des questions relatives à l'économie de la santé, en considérant notamment les liens entre santé et pollution, à l'économie de l'énergie, et plus récemment, dans mes projets, je me suis intéressée à l'économie des ressources naturelles. Des collaborations récentes avec des collègues du CEE-M m'ont également permises d'étendre mes méthodologies de recherche en utilisant l'économie expérimentale et appliquée.

Mon investissement dans l'encadrement d'étudiants et ma participation en tant que membre du projet ANR GREEN-ECON « Vers une économie plus verte : politiques environnementales et adaptation sociétale », porté par Nicolas Quérou et Hubert Stahn entre 2016-2021 ont soutenu ma dynamique de recherche. Ma contribution dans ce projet, illustrée notamment dans les articles de recherche présentés dans ce mémoire, a porté sur l'analyse de différents instruments de politiques publiques pouvant être utilisés pour compenser les externalités environnementales liées à la pollution locale ou globale. Concernant mes implications dans l'encadrement d'étudiants, depuis septembre 2020, je co-encadre avec Francesco Ricci la thèse d'Aurélien Lafrogne qui s'intitule « Le rôle de la finance verte dans la transition énergétique : une perspective macroéconomique », financée par un contrat doctoral de l'Université de Montpellier. Dans ce travail de thèse, le doctorant étudie les mécanismes économiques pouvant justifier le rôle des instruments de finance verte dans le développement d'énergies bas carbones, notamment en présence de défaillances de marché dans l'allocation des fonds par le système financier. Cet encadrement m'a permis de développer plusieurs collaborations autour des thématiques de l'économie de l'énergie. Par ailleurs, j’ai participé à l’encadrement de mémoire d’étudiants de Master 2 de la faculté d’économie.[1]

Dans la suite de ce résumé, je présente synthétiquement les motivations ainsi que les résultats des différents travaux publiés que j’ai mené depuis ma titularisation en 2016 ainsi que mes projets en cours, principalement ceux engagés en lien avec mon co-encadrement de thèse. L’ensemble de ces travaux s’oriente autour de trois axes. Le premier porte sur des problématiques autour des inégalités de santé et de la pollution de l’air. Le second sur des enjeux économiques internationaux liés à la pollution globale. Enfin le dernier porte sur des problématiques inhérentes au financement de la transition énergétique.

1.2. Santé, pollution, inégalités

Dans mes recherches je me suis intéressée à l’impact de l’environnement sur la santé sous le prisme des inégalités. L’analyse des liens entre environnement, inégalité et santé réfère à de multiples interactions et concepts qu’il est important de préciser. Les risques environnementaux pour la santé sont de natures diverses (qualité des eaux, de l’air, des sols) et la pollution atmosphérique est identifiée comme le risque majeur. La Commission Lancet sur la pollution et la santé a indiqué que la pollution de l’air était responsable d’environ 6,7 millions de décès prématurés par an en 2019 au niveau mondial, ce qui correspond à un décès sur huit (voir les résultats présentés dans Fuller et al., 2022). Les hypothèses et formalisations retenues pour mener mes analyses m’ont conduites à considérer ce risque en particulier. Le concept d’inégalités environnementales fait référence à la surexposition de certaines populations à des facteurs de risques environnementaux, ce qui, in fine, est susceptible d’affecter la santé des individus. Cela peut se traduire par des expositions à des niveaux de pollution différents au sein de la population mais aussi par une vulnérabilité aux polluants qui diffère. La source de cette dernière inégalité est intrinsèquement liée aux inégalités socio-économiques et peut trouver son origine dans le profil démographique de la population tout comme dans le profil de revenu. Tout d’abord, les enfants et les personnes âgées ont un "désavantage matériel" qui les rendent plus susceptibles car leur système respiratoire et immunitaire est immature ou fragilisé. Ensuite, au sein d’une même génération, les individus issus de ménages au statut socio-économique inférieur - notamment en termes d’éducation - sont plus vulnérables à la pollution que ceux issus de ménages plus favorisés. Ces différences proviennent du fait que les individus plus riches et plus instruits sont plus susceptibles d’adopter des comportements compensatoires, limitant l’impact des polluants (respect des recommandations lors des pics de pollution par exemple), mais aussi d’investir davantage dans leur santé et celle de leurs enfants (voir, par exemple, Neidell, 2004 et Currie et al., 2014). C’est cette vulnérabilité hétérogène aux polluants, c’est à dire une capacité différente à éviter ou à faire face aux risques environnementaux, que je considère dans ma recherche.

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[1] Les informations détaillées relatives à la direction d’étudiants de Master 2 sont fournies dans la section 6 de ce mémoire.

Une partie de ma recherche a porté sur les effets de la pollution sur le capital humain à long terme et sur les inégalités à travers le canal de la santé des enfants. Les motivations pour considérer les effets de la pollution au plus jeune âge sont doubles. Tout d'abord les évidences empiriques soutiennent la plus grande vulnérabilité des enfants aux polluants de l'air (voir par exemple Sacks et al., 2011, Beatty and Shimshack, 2014 ou WHO, 2018). Ensuite, la littérature économique a identifié l'investissement dans le plus jeune âge comme l'un des leviers les plus efficace qu'un pays puisse utiliser pour réduire les inégalités, étant donné son rendement économique à long terme et sa capacité à améliorer l'équité entre agent. Currie and Almond (2011) recensent les principaux travaux empiriques qui mettent en évidence des conséquences de long terme sur le capital humain d'événements impactant l'environnement de l'agent durant son plus jeune âge. L'explication économique de ces effets de long terme réside notamment dans le concept de complémentarité dynamique dans les stages d'apprentissage, largement discuté depuis Cunha and Heckman (2007), selon lequel le rendement de l'investissement en éducation ou en formation s'accroît avec le développement initial de l'enfant. Une étude publiée en 2016 dans The Lancet, *Advancing Early Childhood Development: from Science to Scale*[2], a permis de recenser les arguments biologiques, physiologiques et économiques pour investir massivement dans le développement des jeunes enfants. Ces conclusions ont des répercussions dans la sphère publique, elles ont notamment impulsé en France des programmes de soutien tel que "périnatalité et petite enfance" de Santé Publique France.

Dans un premier papier avec Emmanuelle Lavaine intitulé **"The Role of Health at Birth and Parental Investment in Early Child Development. Evidence from the French ELFE Cohort", publié dans The European Journal of Health Economics en 2021 (Davin and Lavaine, 2021)**, nous combinons une approche théorique et une approche empirique pour examiner comment la santé à la naissance affecte le développement de l'enfant. En utilisant un modèle théorique simple dans lequel les parents investissent dans le capital de leurs enfants, nous identifions les mécanismes par lesquels une meilleure santé à la naissance peut améliorer le développement de l'enfant. Nous mettons en évidence que le statut socio-économique des parents peut renforcer ou amoindrir la relation entre santé à la naissance et capital humain, en fonction du degré de complémentarité entre les facteurs qui forment le capital humain. Nous réalisons une analyse empirique sur la cohorte ELFE portant sur des enfants nés en France métropolitaine en 2011. ELFE est la première étude scientifique consacrée au suivi régulier d'enfants qui couvre la totalité du territoire métropolitain français sous l'angle des sciences sociales, de la santé et de l'environnement. Les résultats indiquent que l'âge gestationnel affecte positivement l'inventaire de développement de l'enfant, un proxy du capital humain au plus jeune âge. Nous ne trouvons pas d'effet significatif de l'investissement des parents en temps ni d'effet de gravité, selon lequel les effets néfastes d'une mauvaise santé à la naissance sont plus élevés pour les enfants issus

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[2] `https://www.thelancet.com/series/ECD2016`

de familles à faibles revenus ou dont la mère est peu éduquée. Ces résultats encourageant du point de vue du gradient social pour la France n'enlève en rien l'intérêt d'intégrer le développement du jeune enfant dans les politiques de santé. Nous pouvons noter que nous ne faisons pas d'analyse des liens pollution-santé-capital humain au plus jeune âge dans cette étude. Toutefois, nous pouvons inférer un lien entre pollution-santé et capital humain en nous basant sur notre résultat et sur la littérature ayant identifiée une relation causale négative entre l'exposition aux particules fines et la santé des enfants à la naissance. Les économistes ont en effet enrichi les études autour de l'hypothèse des origines fœtales, concept initialement étudié en médecine, en examinant les conséquences d'événements in utero, comme l'exposition à la pollution, sur diverses mesures de santé, sur le capital humain à différents âges ou sur les caractéristiques économiques des agents à l'âge adulte. Les travaux de Almond and Currie (2011) et Almond et al. (2018) fournissent des revues complètes de la littérature empirique sur ces sujets.

Les liens entre pollution, inégalité, et santé des enfants sont examinés précisément dans un second papier avec Karine Constant, intitulé **"Pollution, children's health and the evolution of human capital inequality", publié dans Mathematical Social Sciences en 2021 (Constant and Davin, 2021)**. Ce travail théorique vise à examiner comment la pollution et ses effets sur la santé pendant l'enfance peuvent affecter la dynamique des inégalités entre les ménages. Dans un modèle dans lequel la santé des enfants est déterminée de manière endogène par la pollution et les investissements en santé des parents, nous montrons que l'économie peut présenter des inégalités à long terme et être coincée dans une trappe à inégalités, avec des disparités en constante augmentation, uniquement à cause de la pollution. Nous étudions si une politique environnementale, consistant à taxer la production polluante pour financer des abattements, peut résoudre ce problème. Nous constatons qu'elle peut réduire l'inégalité à long terme et permettre de sortir de la trappe si l'intensité des émissions n'est pas trop élevée et si les disparités initiales en capital humain ne sont pas trop importantes. Dans le cas contraire, nous révélons qu'un policy mix comprenant une subvention supplémentaire aux dépenses de santé peut être une meilleure option, du moins si l'investissement parental dans la santé des enfants est suffisamment efficace.

Dans une seconde partie de ma recherche, j'ai traité la problématique inégalités, pollution, santé, sous un angle différent, en examinant les interactions entre les impacts sanitaires et économiques des épidémies. La pandémie du Covid-19 a accru l'intérêt, déjà existant, de considérer ces interactions mais également de les aborder dans un contexte de dettes publiques grandissantes. En France, comme dans le reste de la zone euro, les mesures budgétaires extraordinaires de soutien à l'activité pendant la crise Covid ont fortement augmenté les ratios de dettes publiques (pour la France la dette publique s'élève à 112,8% du PIB en 2021 contre 97,4% 2019.[3]). Dans un article co-écrit avec Mouez Fodha et Thomas Seegmuller intitulé **"Environment, public debt and epidemics", publié dans Journal of**

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[3] Source INSEE.

Public Economic Theory en 2022 (Davin et al., 2021a) nous étudions si les politiques fiscales, en particulier la dette publique, peuvent contribuer à limiter les conséquences macroéconomiques et sanitaires des épidémies. Notre approche est basée sur trois caractéristiques principales. Premièrement nous introduisons la dynamique des épidémies dans un modèle à générations imbriquées pour tenir compte du fait que les personnes âgées sont plus vulnérables aux effets d'une épidémie. En effet, des études empiriques montrent que la mortalité des patients âgés est plus élevée que celle des patients jeunes et d'âge moyen lors des épidémies, en raison de leur plus grande vulnérabilité. De plus, comme le soulignent Chang et al. (2004), Rust et al. (2009) ou Kontis et al. (2020), les épidémies ont tendance à perturber et à suspendre les services de santé et une telle saturation du système de soins de santé est particulièrement coûteuse pour l'ensemble des patients âgés. Deuxièmement, nous considérons que la dégradation de la qualité de l'environnement augmente le taux de contagion de l'épidémie. Les évidences attestant d'un effet des facteurs environnementaux sur la vitesse de propagation des épidémies sont grandissantes. Le changement climatique a entraîné une prolifération des maladies à transmission vectorielle, comme la malaria, entraînant de fait une augmentation de la transmission (Rohr and Cohen, 2020). La détérioration des écosystèmes concoure à une baisse de l'effet de dilution de la biodiversité et donc à une hausse de l'émérgence et de la propagation de maladies infectieuses (Keesing et al., 2010). Enfin, la pollution atmosphérique est aussi un facteur d'accélération de la transmission des virus entre humains. Les particules de pollution se comportent comme des véhicules pour le transport des virus, en particulier dans les épidémies où le mode de transmission se fait principalement par les aérosols (voir Domingo and Rovira, 2020 pour une revue de la littérature sur le sujet). Par ailleurs, il existe un effet indirect de la pollution sur le taux de propagation, à travers les conséquences de la pollution sur la santé des individus, notamment les plus fragiles. L'exposition à court et long terme à la pollution atmosphérique agit comme un cofacteur de morbi-mortalité car c'est un facteur de risque à l'origine de maladies respiratoires, qui favorise ainsi l'inflammation et diminue la réponse immunitaire de l'organisme face aux infections. Nous considérons donc pour cette analyse des inégalités entre générations résultantes de l'existence d'une épidémie et qui sont alimentées par la pollution. Enfin, nous prenons en compte la politique fiscale et la dette publique dans la discussion, car la gestion d'une crise sanitaire s'accompagne généralement de mesures publiques extraordinaires. Nous montrons que les politiques budgétaires peuvent favoriser la convergence vers un état stable sans maladie. Lorsque les politiques publiques ne sont pas en mesure d'éradiquer définitivement l'épidémie, la dette publique et les transferts de revenus pourraient réduire le nombre de personnes infectées et augmenter le capital et le revenu par habitant. Comme condition préalable, la pollution ne doit pas être trop élevée. Enfin, nous définissons une politique de subvention des ménages qui élimine les inégalités de revenu et de bien-être entre les individus sains et infectés d'une même génération.

1.3. Pollution globale et perspectives internationales

Dans un second axe de recherche, je me suis intéressée aux implications économiques de problèmes environnementaux mondiaux dans un monde globalisé. Outre le changement climatique, les déchets plastiques, les pesticides et les polluants organiques persistants (POP) sont des phénomènes globaux qui peuvent avoir des effets néfastes tant au niveau local que mondial. Pour atteindre une trajectoire cohérente de 2°C, pour limiter le rejet de déchets plastiques dans les océans, ou pour stopper l'accumulation des POP dans l'atmosphère, la communauté internationale appelle à une réponse mondiale immédiate. Bien que mon approche soit suffisamment générale pour aborder la discussion autour de diverses problématiques de pollution globale, le changement climatique est un exemple évident qui représente une menace croissante pour les activités économiques. Comme le souligne le nouveau rapport du groupe de travail II du GIEC (IPCC, 2022a), celui-ci entraîne déjà des pertes substantielles en termes de production et de bien-être de la population ainsi qu'une menace sérieuse pour l'équité intergénérationnelle. Bien que global, le changement climatique et ses conséquences se caractérisent par une forte variabilité d'un pays à l'autre. Le rapport révèle que l'exposition spatiale et temporelle aux impacts du changement climatique augmente dans toutes les régions du monde mais la charge est hétérogène et d'autant plus importante pour les régions les plus vulnérables, où les capacités à mettre en place des mesures d'adaptations sont moindres (voir aussi Mendelsohn et al., 2006 sur l'impact distributif du changement climatique sur les pays riches et pauvres). Plus de 3,3 milliards de personnes vivent dans des pays classés comme très hautement et hautement vulnérables (Afrique de l'Est, Afrique centrale et Afrique de l'Ouest, Amérique centrale, Asie du Sud et du Sud-Est), tandis qu'environ 1,8 milliard de personnes vivent dans des pays à faible et très faible vulnérabilité.Dans un contexte d'interdépendance entre les pays, un tel constat est sans équivoque sur l'intérêt pour les économies relativement peu vulnérables de considérer les problématiques climatiques. Au-delà des considérations d'altruisme et d'équité, il existe des motivations économiques à mettre en place des mesures visant à réduire les dommages pour les économies les plus touchées. Le changement climatique est en effet révélateur des vulnérabilités inhérentes à un monde globalisé. Les risques climatiques peuvent se propager au-delà des frontières nationales, notamment par le biais de flux financiers et du commerce international, ce qui constitue un défi croissant pour les décideurs publics.

Dans une première étude, je me suis penchée sur la transmission des aléas climatiques par le canal du commerce et leurs implications macroéconomiques. Jones and Olken (2010) confirment que des températures plus élevées n'ont pas d'effet direct sur les exportations des pays riches, alors qu'elles réduisent significativement la croissance des exportations des pays pauvres. Toutefois, les régions riches peuvent être indirectement affectées par la hausse des prix et la diminution des quantités de biens importés des régions pauvres. En se concentrant sur le secteur agricole, Costinot et al. (2016) constatent également que les effets néfastes du changement climatique sont atténués lorsque les ajustements de production causés par l'évolution des avantages comparatifs sont pris en en compte. La récente synthèse de travaux de Bednar-Friedl et al. (2022) et l'étude de Challinor et al. (2017) fournissent aussi des évidences sur le fait que les conséquences macroéconomiques du changement climatique sont liées à ses effets sur les flux commerciaux, sur les avantages comparatifs entre pays et, plus généralement, sur le commerce international. Tous ces éléments soulignent donc l'importance d'étudier si et comment les coûts de pollution pourraient être transmis des pays vulnérables vers les pays moins vulnérables par le biais du commerce. Cette question est traitée dans un article co-écrit avec Karine Constant, intitulé **"Unequal vulnerability to climate change and the transmission of adverse effects through international trade", publié dans Environmental and resource economics en 2018 (Constant and Davin, 2019)**. Dans cet article, nous considérons la distribution inégale des dommages causés par le changement climatique dans le monde et nous examinons comment les coûts sous-jacents peuvent se propager d'un pays vulnérable à un pays non vulnérable par le biais du commerce international. Afin de se concentrer sur ces effets indirects, nous traitons ce sujet dans un modèle de commerce Nord-Sud dans lequel le Sud est vulnérable aux dommages causés par la pollution mondiale, tandis que le Nord ne l'est pas. Nous montrons que les impacts du changement climatique dans le Sud peuvent être des sources de perte de bien-être pour les consommateurs du Nord, tant à long terme qu'à court terme. Sur le long terme, une augmentation de la vulnérabilité du Sud peut réduire le bien-être dans l'économie du Nord, même dans le cas où elle améliore les termes de l'échange du Nord. A court terme, la vulnérabilité du Sud peut également représenter une source d'inégalités intergénérationnelles dans le Nord. Par conséquent, nous soulignons les fortes incitations économiques pour les économies non vulnérables - et a fortiori moins vulnérables - de réduire les dommages causés par le changement climatique sur les pays plus vulnérables.

Dans un second article, je me suis intéressée aux interactions entre dette publique et problèmes environnementaux globaux. La classification fournit par le FMI et la Banque Mondiale concernant la soutenabilité des dettes[4] suggère qu'une grande partie des pays à faible revenu présente un risque élevé de connaître une crise de la dette, soulignant ainsi l'importance de composer avec les profils d'endettement des pays pour relever les défis environnementaux. La question de la dette publique, plus précisément du taux d'endettement public, et de ses implications dans le financement de la transition écologique est d'ailleurs abordée par le groupe de travail III du GIEC (IPCC, 2022b). Les défis environnementaux sont aggravés par des niveaux élevés de vulnérabilité économique externe, en partie caractérisée par des dettes publiques coûteuses. Les pays vulnérables recourent de manière récurrente à la dette publique pour absorber l'impact des chocs macroéconomiques externes et, depuis peu, de catastrophes naturelles plus fréquentes. La crise du Covid-19 tout comme la hausse des événements climatiques extrêmes a réduit davantage la marge de manœuvre budgétaire de nombreux gouvernements en accroissant la probabilité de tension lié à la dette

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[4] Voir `https://www.worldbank.org/en/programs/debt-toolkit/dsa`

souveraine. Tandis que de nombreux pays vulnérables étaient déjà caractérisés par un accès plus faible à l'épargne globale et/ou à des coûts de financement plus élevés, la hausse de leur endettement apparaît comme un frein supplémentaire pour le financement de la transition et de l'adaptation. Les interactions entre dette publique et problèmes environnementaux globaux peuvent ainsi faire références aux effets positif et significatifs de la vulnérabilité climatique sur les rendements souverains (Buhr et al., 2018) et donc à l'idée qu'il existe un cercle vicieux dans lequel la vulnérabilité est auto-entretenue par le canal du financement de la dette publique. Elles peuvent aussi simplement référer au fait que les niveaux élevés de dette publique modifient la pression fiscale et contraignent les investissements nécessaires à une croissance durable, notamment par des effets d'éviction qui freinent l'accumulation de capital. Ainsi la capacité des pays à faire face aux vulnérabilités et à atténuer la pollution évolue avec le taux d'endettement. Je considère cette seconde approche dans un papier co-écrit avec Mouez Fodha et Thomas Seegmuller intitulé **"Pollution in a globalized world: Are debt transfers among countries a solution?", publié dans International Journal of Economic Theory en 2022 (Davin et al., 2021b)**. Dans ce travail, dans lequel nous considérons les effets économiques et environnementaux d'un transfert de dette des pays riches vers les pays pauvres, c'est-à-dire une diminution de la dette publique d'un pays à faible revenu financée par un pays à revenu élevé.[5] La contribution des pays développés au financement du climat et leur soutien financier aux pays pauvres est un engagement institutionnel inclut dans les différents accords climatiques. Ceux-ci sont motivés par des questions de justice sociales et économiques. Lorsque l'on examine la diversité des instruments utilisés pour financer le climat, les transferts de dette ne représentent qu'une proportion insignifiante des stratégies de financement. Pourtant, dans un contexte où aucune politique environnementale internationale n'a été mise en œuvre pour lutter efficacement contre le changement climatique l'examen des effets de leviers de politiques économiques classiques, comme un transfert de dette, nous semble justifié. Dans notre modèle les habitants du pays à revenu élevé sont supposés les plus patients. Dans le cadre d'une mobilité parfaite des actifs entre les pays, nous montrons que le transfert augmente le stock de capital global et la qualité de l'environnement lorsque les abattements publics sont suffisamment efficaces. Le bien-être des deux pays peut également s'améliorer. En revanche, dans un contexte de faible mobilité des actifs, et donc d'un accès aux marchés internationaux des capitaux limité, le transfert n'accroît pas le capital dans le pays le plus riche tandis que la qualité de l'environnement peut encore s'améliorer. Cela provient d'un effet d'éviction de la dette dans le pays à revenu élevé qui surgit dès lors que la hausse de la dette ne peut pas être financée totalement par l'épargne excédentaire de l'autre pays.

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[5] L'analyse du cercle vicieux pouvant exister entre vulnérabilité aux changements climatiques et vulnérabilité de la dette souveraine fait partie de mes projets de recherche, que je n'aborde pas dans cette introduction mais qui sont développés dans la Section 4.4.

1.4. Finance verte et transition énergétique

Cette partie est dédiée à la présentation synthétique des travaux en cours que je mène sur la thématique de la transition énergétique. J'ai notamment approfondi cette thématique dans le cadre d'un co-encadrement doctoral, et les travaux présentés ici n'ont à ce jour pas encore donné lieu à des publications. Ils ont été diffusés en conférence, workshop ou séminaire durant l'année 2022.

L'objectif de 2°C requiert une réduction des émissions de gaz à effet de serre de 43% d'ici 2030 et de 84% d'ici 2040 par rapport à 2019 (IPCC, 2022b). Or, en 2021, la part des énergies fossiles dans l'énergie primaire est de 82,28% au niveau mondial, 70,42% au niveau de l'UE et de 49,87% en France. Une transition majeure et rapide du système énergétique est donc impérative. Au niveau de l'UE, la commission a proposé un plan cible en matière de climat à l'horizon 2030 avec pour objectif une réduction des émissions de gaz à effet de serre d'au moins 55% par rapport aux niveaux de 1990 d'ici à 2030. L'Agence internationale pour les énergies renouvelables (IRENA) estime qu'un investissement moyen de 73 milliards de dollars par an dans les énergies renouvelables est nécessaire pour atteindre cet objectif (IRENA, 2018). Les autorités publiques jouent un rôle central dans la promotion de ces investissements notamment par le biais de politiques incitatives visant à soutenir l'attractivité des investissements privés dans les énergies renouvelables. Le financement privé est en effet nécessaire à la transition vers une énergie à faible intensité carbone. Une analyse des structures de financement de la transition énergétique par l'IRENA montre qu'en 2019, 80% du total des investissements dans le secteur de l'énergie était privé.

La théorie économique a largement identifié la tarification du carbone comme une politique centrale pour générer un signal prix, permettant ainsi les changements nécessaires pour atteindre les objectifs de stabilisation du climat (voir par exemple Stiglitz et al., 2017). Néanmoins, le débat public et académique sur la politique climatique a souligné la nécessité de compléter la tarification carbone par d'autres instruments de politique environnementale et énergétique (Steckel and Jakob, 2018). Les arguments en faveur de ces interventions reposent notamment sur l'existence d'imperfections de marché, outre l'externalité environnementale qui pourrait être corrigée par la seule tarification carbone. Les défaillances de marché dans le processus de création et d'allocation du crédit par le système financier représente un frein sérieux (Campiglio, 2016). Je m'intéresse à cette défaillance en particulier dans mes recherches, soutenue par plusieurs évidences empiriques montrant que les contraintes de crédit déforment la composition des actifs en faveur d'un surinvestissement dans les actifs à forte intensité carbone (Andersen, 2017, Noailly and Smeets, 2021, Papoutsi et al., 2021, De Haas et al., 2021). Il apparaît donc important de ne pas considérer les politiques climatiques isolément de l'environnement général des investissements et de porter une attention particulière aux mesures de finance verte visant à améliorer les conditions d'accès au financement pour l'investissement bas carbone. Le concept de finance verte est un concept de longue date, promu avec l'adoption de l'Accord de Paris sur le climat, qui fait référence aux mesures et instruments financiers, comme les *green bonds*, favorisant le financement de la transition écologique. L'idée sous-jacente à ces instruments est qu'ils pourraient être associés à un *greenium* positif. Le *greenium* renvoie à la différence de coût entre une activité qui implique des émissions carbones et une activité alternative qui est "verte". Lorsque l'investisseur est dotée d'une conscience environnementale, il a une exigence de rendement plus faible pour des projets bas carbones ce qui permet à l'émetteur de l'obligation verte de se financer à moindre coût. Dans une première recherche théorique, menée avec Aurélien Lafrogne et Francesco Ricci, nous considérons une économie avec des imperfections sur le marché du crédit, où les rentes des propriétaires de ressources naturelles dites "brunes" offrent un collatéral aux producteurs d'énergie carbonée, qui bénéficient ainsi d'un avantage sur le marché du crédit. Cela, combiné à un besoin en capital plus élevé dans le secteur "vert", implique un biais d'investissement en faveur des entreprises brunes dans le secteur de l'énergie. Dans ce contexte, il peut coexister dans l'économie deux équilibres, dont l'un d'entre eux se caractérise par des rentes de ressources plus importantes, un meilleur accès au crédit pour les firmes brunes, une part carbonée plus importante dans le mix énergétique et un surplus global plus faible. L'introduction d'instruments financiers spécifiques, tels que les obligations vertes, déplace l'épargne vers les actifs verts en réduisant le coût de l'emprunt pour les entreprises vertes (i.e. génère un *greenium*). On peut alors observer un effet structurel : un *greenium* suffisamment important élimine le biais, supprimant ainsi l'équilibre relativement plus carboné et moins efficace. En outre, le développement de la finance verte réduit la part brune du mix énergétique. Notre analyse clarifie les mécanismes économiques à l'œuvre, et identifie les conditions pour des effets distincts, structurels plutôt que marginaux.

Dans une seconde analyse, empirique, conduite avec Aurélien Lafrogne et Thi Hong Van Hoang nous portons notre attention sur le risque de transition associé à un événement lié à la politique climatique. Le risque de transition climatique réfère aux effets, sur la valeur des entreprises, des évolutions réglementaires et politiques visant à mener les économies vers de faibles émissions carbones. Le risque de transition constitue une préoccupation particulière pour les entreprises qui dépendent davantage d'une production ou d'une consommation à forte intensité carbone (Battiston et al., 2021). Au contraire, les firmes s'engageant dans la transition devraient être moins sensibles. Nous souhaitons tester cette conjecture, en nous basant sur le résultat de Flammer (2021) selon lequel l'utilisation de *green bonds* comme instrument de financement par les firmes donne un signal crédible sur leurs engagements environnementaux. Notre analyse a donc pour objet de déterminer si l'émission d'obligations vertes permet aux entreprises de se couvrir contre le risque de transition. Nous considérons les entreprises européennes de l'indice Eurostoxx 600 et examinons leur réaction suite à la présentation du paquet "Fit for 55" (FF55) par la Commission européenne en Juillet 2021. Cet événement capte un signal important concernant l'engagement public européen sur les actions climatiques. Le paquet comprend un ensemble de propositions liées et complémentaires, dont la réforme du système européen d'échange de quotas d'émission, qui vise à augmenter les prix du carbone. Une étude d'événement est utilisée pour examiner la réaction du prix de l'action des firmes à la présentation du FF55. Nous obtenons que le fait d'être un émetteur d'obligations vertes a un effet positif sur le rendement anormal généré par l'événement politique. En outre, des résultats préliminaires montre que la part d'obligations vertes par rapport à l'actif total de la firme joue favorablement sur le rendement anormal lorsque la firme a un effet de levier important. Nos résultats suggèrent donc que l'émission d'obligations vertes peut agir comme une couverture contre le risque de transition. D'autres facteurs ont également une relation significative avec les rendements anormaux générés par l'annonce de l 'annonce de la politique, tels que la taille et la structure du capital de l'entreprise, tandis que le profil d'émetteur de gaz à effet de serre n'a pas d'effet significatif.

La suite de ce mémoire est rédigée en anglais et présente de façon détaillée mes recherches publiées, en Sections 2 et 3, ainsi que mes projets de recherche, en Section 4. La Section 5 conclut ce mémoire et mon curriculum vitae est fournit en Section 6.

2. LOCAL ENVIRONMENTAL ISSUES, INEQUALITY AND HEALTH

In my research, I have been interested in the unequal impact of the environment on health to understand the interplay between economics and the environment. The analysis of the links between the environment, inequality and health refers to multiple interactions and concepts that it is important to specify. Environmental risks to health are diverse in nature (water, air and soil quality) and air pollution is identified as the major risk. There is considerable evidence that air pollution, has a positive and significant effect on morbidity - i.e. the rate of disease in the population - and mortality - i.e. the rate of death.[6] The Lancet Commission on Pollution and Health has recently indicated that air pollution is responsible for approximately 6.7 million premature deaths per year in 2019, which corresponds to one in eight deaths worldwide (Fuller et al., 2022). We consider this risk in particular to formulate our models and assumptions in papers presented in this thesis. Then, the concept of environmental inequality refers to the overexposure of certain populations to environmental risk factors, which, in the end, is likely to affect the health of individuals. This may be reflected in different exposures to pollution levels within the population but also in different vulnerabilities to pollutants. The source of the latter inequality is intrinsically linked to socioeconomic inequalities and can be traced back to the demographic profile of the population as well as the income profile. First, children and the elderly have a "material disadvantage" that makes them more susceptible because their respiratory and immune systems are immature or compromised. Second, within a generation, individuals from households with lower socioeconomic status - especially in terms of education - are more vulnerable to pollution than those from more advantaged households. This is particularly true for children (see, for example, Neidell, 2004 or Currie, 2009). In particular, it appears that the income gap in households with children translates into relative disadvantage early in life by affecting child development before age five (see e.g., Almond et al., 2018, who provide an explanation on how human capital develops during the early years.) These differences arise because wealthier and better-educated parents are more likely to provide a nurturing environment for their children, but also to invest more in their children's health (see, for example, Currie et al., 2014). In my research I pay a particular attention to this heterogeneous vulnerability to pollutants, i.e., a different ability to avoid or cope with environmental risks.

2.1. Child's health, pollution and human capital inequalities

Part of my research has focused on the effects of pollution on long-term human capital and on inequalities through the channel of children's health. The motivations for considering the effects of pollution at an early age are twofold. First, empirical evidence supports the greater vulnerability of children to air pollutants (see, for example, Sacks et al., 2011, Beatty

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[6] See, e.g., Ostro, 1983 ; Hanna and Oliva, 2015 ; Graff Zivin and Neidell, 2012 on the effect of air pollution on morbidity and Bell and Davis, 2001 ; Pope Iii et al., 2002 ; Evans and Smith, 2005 or Beelen et al., 2014 on its effect on mortality.

and Shimshack, 2014). Empirical studies identify that these larger effects are due to both a larger vulnerability of children, mainly because their lungs, brains and immune system are not completely developed, and a larger exposure, as they spend more time engaging in physical activity outside - where air pollution levels are usually larger (see e.g., Bateson and Schwartz, 2007). Second, detrimental effects on children's health are not only a short-term issue but persist later in life (see Currie et al., 2014 for a literature review). Childhood exposure to pollution is found to be associated with poor adult health. Moreover, by increasing school absenteeism (see e.g., Park et al., 2002) and affecting negatively cognitive and learning abilities of children (see e.g., Factor-Litvak et al., 2014), environmental degradation deteriorates also human capital formation. Through all these channels, the exposure of children to pollution implies long-term negative consequences on human capital and income when adult, representing a persistent threat to the well-being and abilities of individuals. Indeed, human capital plays a vital role in an individual's income potential but also in determining he wealth of nations and their level of development.[7] The economic literature has thus identified early childhood investment as one of the most effective levers a country can use to reduce inequality, given its long-term economic returns and its ability to improve equity among agents. The economic explanation of these long-run effects lies in particular in the concept of "dynamic" complementarity in learning placements, widely discussed since Cunha and Heckman (2007), according to which the return on investment in education or training increases with the initial development of the child. These conclusions have repercussions in the public sphere, and in France they have led to support programs such as "perinatality and early childhood" of Santé Publique France.

In a paper with Emmanuelle Lavaine entitled **"The Role of Health at Birth and Parental Investment in Early Child Development. Evidence from the French ELFE Cohort", published in The European Journal of Health Economics in 2021 (Davin and Lavaine, 2021)**, we combine a theoretical and an empirical approach to address how health at birth affects French children's cognitive development at a very early age and how this effect differs between socio-economic groups. More specifically, we adopt a theoretical and empirical approach to identify the impact of birth weight and gestational age on child development at the age of one year. We consider optimizing parents' behaviors to theoretically assess the effect of health at birth on child development and to examine if and how health endowment and parental socioeconomic conditions interact to form child human capital. We also consider a non-random assignment of health at birth when conducting the empirical analysis. Focusing on the interplay between health and family environment, part of the literature attempts to examine if poor health conditions affect children's development differently across socioeconomic groups. There is no clear consensus emerging from existing studies. Case et al. (2002)

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[7] The Manuelli and Seshradi' paper attempted to explain the income differences between countries. They focused on the human capital in each country and provided a new way to measure it. They found that cross-country differences in average human capital per worker were much larger than that suggested by previous studies. They concluded that a large part of the cross-country differences in wealth could be explained by differences in human capital quality.

examine health outcomes in the US and found that the negative health impact of chronic health conditions in early life is more pronounced in low-income families. In contrast, Currie and Stabile (2003) find that the effect of a health shock on Canadian children's test scores and future health does not differ across socioeconomic groups. A recent study of Wei and Feeny (2019) confirm this result. Authors found no evidence that Canadian children from low-income families suffered more from poor health at birth than those of high-income families. In the UK, no evidence was found that social background modified the effect of birth weight on cognitive development (Jefferis et al., 2002).[8] While these studies do not provide a clear theoretical foundation to explain the economic intuition behind their results, we use theory to identify the mechanisms behind such interactions and appreciate how poor health at birth can inhibit skill formation. We first develop a simple theoretical model based on parental investment in children, in line with the models of human capital formation proposed by Cunha et al. (2010). Parents being rational and aware that they can affect their children's development, invest a part of their time and financial resources to this purpose. Returns on this investment depend on parental socioeconomic status and the health status of their children. In this way, the child's endowment affects the behavioral responses of parents. Thus, considering optimizing parents' behaviors in the form of time spent with children, health at birth affects human capital through two channels. On the one hand, health at birth can affect children's development directly through a purely biological effect that increases the risk of learning disabilities, academic difficulties, or behavioral problems. On the other hand, parents' engagement in children's development depends on their birth endowment. This indirect effect of health at birth on child human capital can be positive or negative, depending on how child human capital is formed. We assume a general formalization in the theoretical part to discuss the different possible cases and to identify the global effect of child's birth endowment. We predict that health conditions at birth would improve early child development and that parental behaviors can mitigate or amplify this relationship. Concerning the influence of a family's environment on the adverse effect of bad health endowments at birth, we conclude that affluent families suffer less when birth endowments and family's wealth are substitutes in forming early childhood human capital. We then conduct an empirical analysis to test our prediction for France, using a unique dataset on the ELFE cohort's entire French territory. We aim at empirically analyzing the consequences of gestational age and birth weight on child development measured at one year. Moreover, we aim to shed light on differential impacts according to the income and education of the mother. There are several empirical challenges in estimating health's causal effect at birth on child development outcomes. In particular, some omitted variables may be influencing both exposure and outcome. In our analysis, health at birth may be correlated with other factors, such as wealth, which may also be correlated with child development, generating a

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[8] Not that it is difficult to give an indisputable explanation for the differences observed across countries as outcomes, explanatory variables, and the periods analyzed differ in each study. Nevertheless, their results may suggest less equitable access to child health care in the US.

potential omitted variable bias problem (Shiko and Eskil, 2019). Therefore, if wealthier families are sorting themselves into residential locations with good health conditions, a naive ordinary least squares (OLS) analysis may overestimate health's actual effect. To mitigate such issues and to infer the impact of health at birth on child development, we first use a rich set of socio-demographic control variables available in the ELFE database. Then, in line with the literature that reports seasonality in the birth outcome, we use the season of birth as an instrumental approach. The intuition to use season of birth as an instrument relies on the fact that it induces seasonal differences in maternal exposure to viral infections, meteorological factors, air pollution, food supply, physical activities, or diet, that directly affects health at birth, independently of parental characteristics (see e.g., Strand et al., 2011, for a recent review of the epidemiological evidence on seasonality of birth outcomes).[9] To dissociate the parental investment effect from the biological impact identified in the theoretical part, we then question whether parental time investment is related to health at birth. From our results, we identify an effect of gestational age on early child development, mainly due to biological effect. Indeed, our results suggest that parental behavior does not depend significantly on a child's health at birth. Birth weight is not a relevant determinant of child development in our study, in line with the analysis of Conti et al. (2020), which underlines that birth weight is not informative as it can capture negative and positive aspects of fetal health. Finally, we cannot conclude that there are inequalities in the impact of health at birth on child development for France, as we find no significant difference depending on the parents' revenue or education profiles of the mother. Our results show no heterogeneous effect among socioeconomic factors suggesting an efficient treatment of health issues at very early age. In this research, we do not analyze the dual link between environmental heath and human capital at the youngest age in this study. However, we can infer a link between pollution, health and human capital based on our result and on the literature that has identified a negative causal relationship between exposure to fine particles and children's health at birth.

In a paper with Karine Constant, entitled **"Pollution, children's health and the evolution of human capital inequality", published in Mathematical Social Sciences in 2021 (Constant and Davin, 2021)**, we adopt a theoretical approach to question the potential role of childhood exposure to pollution in the intergenerational transmission of income inequality among agents. In this paper, we aim at examining how this mechanism could occur, what would be the consequences, and therefore, whether environmental policies could be a part of the solution to overcome the inequality issue. We focus on the dynamics of wealth inequality across generations as it represents a major challenge for our society. Since 1980, the gap between rich and poor is at its highest level in most developed countries and follows an upward trend (see, e.g. UN, 2020). Sources of these disparities are multidimensional and concern economic, social and health dimensions. Large health inequalities exist in the

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[9] In this vein, Currie and Schwandt (2013) underlined that higher influenza prevalence in January and February explains an increase in prematurity of more than 10% during these months.

population according to the socioeconomic status of individuals. People in the lowest education category are twice more likely to view their health as poor compared to those with tertiary education (see, e.g. Raghupathi and Raghupathi, 2020). These disparities may entail huge costs for society - in terms of well-being, health and social costs, productivity loss, discouraged investments, wasted potential *etc*. Moreover, a growing number of empirical and theoretical studies emphasize the net detrimental effect of inequality on long-term economic growth in rich countries through its negative effect on average human capital accumulation (see, e.g., Galor, 2011, Brueckner and Lederman, 2018 or Constant, 2019). For all these reasons, reducing these disparities has become an explicit objective for many governments and motivate my interest in exploring the different channels through which they occur. To study the potential role of the health effect of pollution during childhood in the transmission of inequality, we formalize an overlapping generations model, with children and parents, in which agents are heterogeneous in terms of human capital. In accordance with the results emphasized by the literature discussed earlier, we consider the effect of air pollution on children's health, the possibility for parents to invest in health care to lower this adverse effect, and the role of children's health in the acquisition of human capital. Through a theoretical analysis and a numerical illustration, we find that the economy may exhibit different long-term behaviors according to the pollution intensity of production and the initial level of disparities between agents. When they are both sufficiently low, the economy converges toward a long-term state without inequality. However, if production is highly polluting, inequality will always persist across time - whatever the initial level of inequality - and the economy may even be caught in an inequality trap with steadily rising disparities. The underlying mechanism is the following. Parents choose the level of expenditure aiming at reducing the health effects of pollution. Their human capital being heterogeneous, so are their financial abilities and their investments, which entails a heterogeneous vulnerability to pollution among children. Pollution affects more children from poorer households, who will therefore be less able to accumulate human capital and have a lower return on the education investment. Thus, the gap among households increases at each generation due to pollution. Note that we obtain this result despite the fact that we consider no difference in terms of abilities and diminishing marginal returns of human capital accumulation that usually ensure the absence of inequality in the long run. Here, such equality would always be found without pollution. But in the presence of pollution, its detrimental effect on children's health may dominate and hence prevent human capital convergence in the long run. Thus, the exposure of children to pollution represents an important channel of intergenerational transmission of inequality.

We then explore if specific public interventions focusing on this mechanism are effective to tackle these human capital inequalities. First, pollution being the source of increasing divergence between agents, we examine the consequences of an environmental policy that consists in public maintenance financed by a tax on polluting production. Then, we also study the effects of a combination of an environmental and a health policy, through private health subsidy financed by a production tax. We obtain that an environmental policy is a good option to reduce the inequality issue in the economy but only when pollution intensity and the initial level of disparities among agents are not too high. Otherwise, it is not sufficient and may even reinforce inequality due to the negative income effect of the tax. In this case, we reveal that adding a health policy to the policy package could be an interesting solution. Typically, when health expenditure is sufficiently determining for health with respect to pollution, such a policy mix can prevent the economy to exhibit rising inequalities for a larger set of emission intensity.

2.2. Epidemics, pollution and intergenerational inequality

In my research, I have addressed the interplay between economy and the environment through another health channel, that of epidemics. The Covid-19 pandemic has increased the interest, already existing, to consider the interactions between epidemics and economy but also to approach them in a context of growing public debt.[10] In France, as in the rest of the eurozone, the extraordinary budgetary measures to support activity during the Covid crisis have sharply increased public debt ratios. For other diseases like HIV or malaria, debt relief are frequently mentioned as instrument to help endemic countries to control epidemics (see Snow et al., 2010 and Abah, 2020). This illustrates that debt management is expected to play a crucial role to try to control or eradicate an epidemic and how managing a pandemic to limit health and economic costs is challenging.

Without restricting our attention to a particular epidemic, we analyze in a paper with Mouez Fodha and Thomas Seegmuller entitled **"Environment, public debt and epidemics", published in Journal of Public Economic Theory in 2022 (Davin et al., 2021a)** the effects of public interventions to control a disease, in particular health public spending and fiscal policy with public debt. Our approach differs from existing studies as we consider three main features. First, we introduce the dynamics of epidemics in an overlapping generation model to take into account the unequal effect of epidemics among young and old agent. Empirical studies show that the mortality of elderly patients is higher than that of young and middle-aged patients during epidemics, due to their greater vulnerability. Taking the recent example of Covid-19, elderly patients are more likely to progress to severe disease (see e.g., Liu et al., 2020, Williamson et al., 2020). Moreover, as underlined by Chang et al. (2004), Rust et al. (2009) or Kontis et al. (2020) epidemics tend to disrupt and suspend health services and such a saturation of the health care system is particularly costly for vulnerable elderly patients. Second, we consider that degradation of environmental quality increases the rate of epidemic contagion. There are growing evidences of an effect of environmental factors on the rate of spread of epidemics. The deterioration of ecosystems contributes to a decrease in the dilution effect of biodiversity and thus to an increase in the emergence and

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[10] The literature interested in the analysis of the interactions between economics and epidemics is large (see for example Boucekkine et al., 2009, Boucekkine and Laffargue, 2010) and has obviously been revived and adapted to the specificities of the Covid-19 (see for example Acemoglu et al., 2021, Goenka et al., 2021).

spread of infectious diseases (Keesing et al., 2010). Indeed, this effect explains the probability of the virus appearing (impulse source), but also its contagiousness. As Augeraud-Véron et al. (2021) point out, the decline in biodiversity leads to an increase in the prevalence and transmission rates at the local level and to a selection effect of the most harmful pathogenic strains. The process of selecting increasingly resistant and dangerous variants explains their ability to spread more easily among populations.[11] Climate change has also led to a proliferation of vector-borne diseases, such as malaria, resulting in increased transmission (Rohr and Cohen, 2020). Air pollution (mainly PM and NO_2) is also a factor in accelerating the transmission of viruses between humans. Pollution particles act as vehicles for the transport of viruses, particularly in epidemics where the mode of transmission is primarily by aerosols (see Domingo and Rovira, 2020 for a review of the literature on the subject). In addition, there is an indirect effect of pollution on the rate of spread, through the consequences of pollution on the health of individuals, especially the most fragile. Short- and long-term exposure to air pollution acts as a co-factor of morbidity and mortality as it is a risk factor for respiratory diseases. As a result, it promotes inflammation and decreases the body's immune response to infections. We therefore consider for this analysis inequalities between generations face to an epidemic which is fed by pollution. Finally, we take into account fiscal policy and public debt in the discussion, while public actions examined in the literature dealing with epidemics and economics is greatly based on confinement, social distancing and the speed at which a vaccine develops.

In our model there are three-period lived households with young inactive agents, working adults and old retirees. The dynamics of epidemics are formalized by introducing a SIS (susceptible–infected–susceptible) model, in line with Bosi and Desmarchelier (2020) or Goenka and Liu (2020). Because of epidemics, the older agent bears a premature risk of death while the adult agent will be sick, without fatal consequences, but will have to take time off work what entails a variation of revenue. We consider that degradation of the environmental quality increases the rate of contagion of the epidemic. Finally, health policy consisting in public spending to prevent, detect, control and treat quickly the epidemics, contributes to push down the contagion rate. The government finances health expenditures and paid sick leave for infected workers, through taxation of income, but also through the issuance of public debt. In line with Geoffard and Philipson (1997),[12] we assume that health policy reduce the transmission of the virus but does not allow to have full immunity.

We obtain a stable steady state which is endemic, i.e characterized by the presence of the virus. However, the government can increase health expenditures to slow down the spread of the virus. Such a strategy can allow to rule out the endemic steady state and converge to a disease-free steady state. These results are conditioned by the pollution intensity of pro-

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[11] Augeraud-Véron et al. (2021) link biodiversity conservation, the risk of pandemics, economic dynamics and mitigation policies. We adopt a different perspective in our study.

[12] Even if public funds are directed towards the development of a vaccine, Geoffard and Philipson (1997) underline the difficulties for policies to increase demand for vaccine and hence to achieve eradication with vaccine.

duction: the higher the pollution intensity, the more difficult it is to fight the epidemic. If the public policy is not able to remove entirely the epidemic, the economy converges towards an endemic steady state. It could however be used to reduce the number of infected people and increase capital per capita in the long run endemic equilibrium. The complexity of the interactions between fiscal policy and the fight against epidemics is highlighted. In fact, on the one hand, any increase in public debt leads to a crowding-out effect on productive capital. The latter implies a drop in production, wages, savings and tax revenues, which curbs the expected effects of increased public spending, and reduces the effectiveness of public policy. At the same time, it also slows down pollution and plays a positive role in the fight against the virus. On the other hand, the increase in debt allows an increase in public spending, and thus a slowing of the epidemic, which has a stimulus effect on the economy through the increase in the number of workers, savings and capital (crowding-in effect). The final outcome depends on the relative magnitude of these two channels. We show that the crowding-in effect dominates if the rate of pollution emission is not too high. At the endemic steady state, there are income inequalities between infected and healthy people. We show that it is possible to design an appropriate redistribution income policy to address this welfare disparities. This policy consists of a differentiated transfer of income for workers and the sick. It complements the public policy to combat the virus. We emphasize that such intervention can be costly for healthy people when public budget for transfers is not sufficiently important.

3. GLOBAL ENVIRONMENTAL ISSUES AND INTERNATIONAL PERSPECTIVES

In a second line of research, I am interested in the economic implications of global environmental problems in a globalized world. In addition to climate change, plastic waste, pesticides and persistent organic pollutants are global phenomena that can have adverse effects both locally and globally. While my approach is broad enough to address the discussion around various global pollution issues, climate change is an obvious example that poses a growing threat to economic activities and for which the international community is calling for an immediate global response. As the new IPCC Working Group II report points out, climate change is already causing substantial losses in production and population welfare as well as a serious threat to intergenerational equity. Although global, climate change and its consequences are characterized by high variability across countries. It will thus increase existing economic inequalities and cause some populations to fall into poverty trap. The report reveals that spatial and temporal exposure to climate change impacts is increasing in all regions of the world, but the burden is heterogeneous and more important for the most vulnerable regions where the capacity to implement adaptation measures is lower (see also Mendelsohn et al., 2006 on the distributive impact of climate change on rich and poor countries). More than 3.3 billion people live in countries classified as highly and very highly vulnerable (East, Central and West Africa, Central America, South and Southeast Asia), while about 1.8 billion people live in countries with low and very low vulnerability.[13] In a context of interdependence between countries, such a finding is unequivocal on the interest for relatively non-vulnerable economies to consider climate issues. Beyond considerations of altruism and equity, there are economic incentives to implement measures to reduce damage for the most affected economies. Indeed, climate change reveals the vulnerabilities inherent in a globalized world. Climate risks can spread beyond national borders, including through financial flows and international trade, posing a growing challenge to policymakers.

3.1. *Trade, the environment and unequal vulnerability*

In a first study, I am interested in the economic impacts of local climate effect that can spread and propagate through international trade. I attempt to examine if and how trade flow can make local climatic damage global. Trade is recognized as a key mean to fight poverty and achieve the United Nation Millennium Development Goals, specifically by improving developing countries access to markets. International trade is also view as a key driver of productivity and economic growth, and a source of technologies diffusion whose impact on global emission can be contrasted (see Ing and Nicolaï, 2020). Regarding the interplay between trade and climate change, several empirical studies reveal that the international trade conditions the effect of climate change. Jones and Olken (2010) obtain that from 1950 to 2006 higher temperatures do not have a direct effect on the exports of rich countries, while they significantly reduce the growth of exports from poor countries. However, richer regions may be indirectly affected by higher prices and lower quantities of goods imported from poor regions. Focusing on the agricultural sector Costinot et al. (2016) find that the adverse effects of climate change are mitigated when production adjustments caused by changes in comparative advantage are taken into account. The recent survey by Bednar-Friedl et al. (2022) and the studies by Schenker (2013) and Challinor et al. (2017) also provide evidence that the macroeconomic consequences of climate change are related to its effects on trade flows, on comparative advantages between countries and, more generally on international trade. All these elements therefore underline the importance of studying whether and how pollution costs could be transmitted from vulnerable to less vulnerable countries through trade. This question is addressed in an article co-authored with Karine Constant, entitled **"Unequal vulnerability to climate change and the transmission of adverse effects through international trade", published in Environmental and resource economics in 2018 (Constant and Davin, 2019)**.

We are using a dynamic general equilibrium model with overlapping generations. We formalize two regions, North and South, representing developed and developing countries respectively. They can produce and trade two goods - a green good and a brown good whose

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[13] Chapter 8 of IPCC Working Group II details the methodology used to measure country vulnerability according to the INFORM risk index and the components of the WorldRiskIndex.

production generates pollution emissions. The stock of pollution, which evolves over time with economic activity, is responsible for damages unequally distributed around the world. There is a risk - increasing with the pollution stock - that extreme events destroy a share of the production as in Golosov et al. (2014) and Dietz and Stern (2015). In this paper, we do not examine the uncertainty associated with extreme weather but focus on the deterministic effect of pollution on economic activity. Therefore, our pollution damages can also represent the productivity loss associated with the increase in temperature (see, e.g., Dell et al., 2012 or Burke et al., 2015). To take into account the significant difference in terms of vulnerability between countries in a simple way, we assume that South is the only region that suffers from the direct damages due to climate change, while North is non-vulnerable. The following diagram illustrates the model.

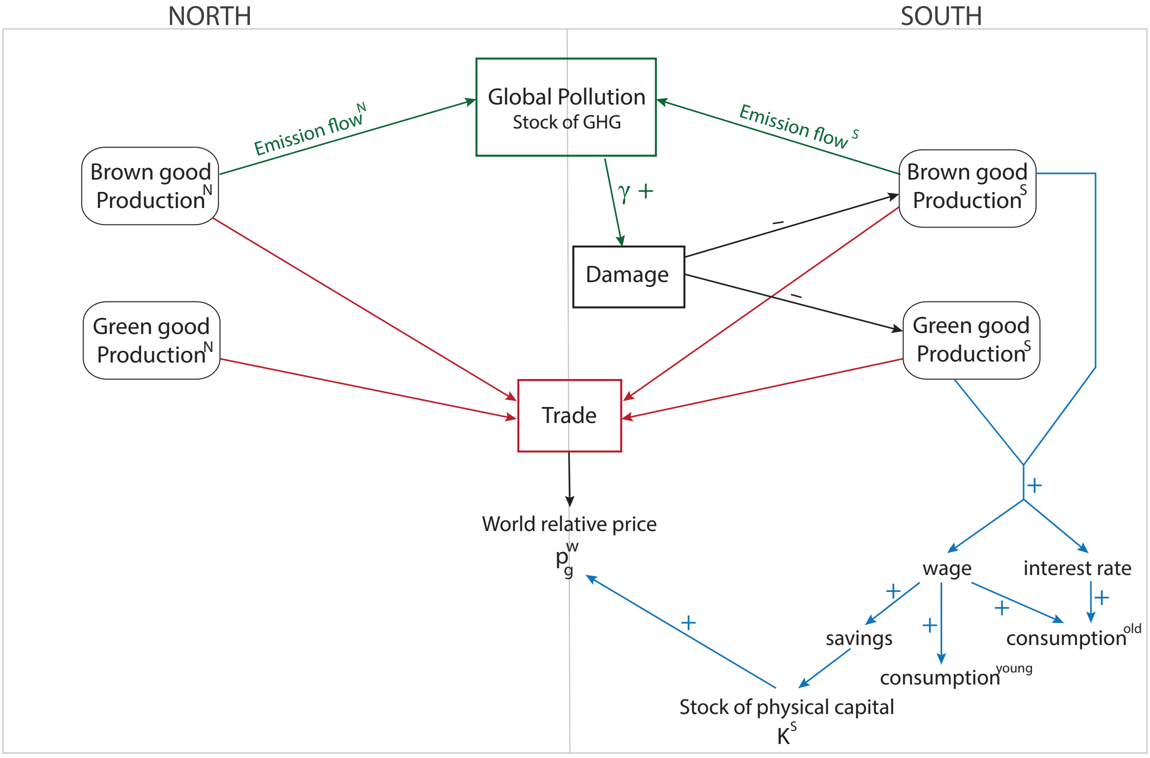

Figure 1: Structure of the model

With this dynamic model, we determine that the lifetime welfare of northern agents evolves across time until the economy converges to its long-term state. When the South's production is altered by climate change, the usual positive trend in welfare resulting from capital accumulation is questioned for both countries. More precisely, in the South region, climate damages negatively impact the net output of firms, and hence the remuneration of production factors and capital accumulation. By making capital scarcer, pollution affects world prices and entails a negative income effect on northern agents. When pollution becomes too high, so does the extent of this negative effect. Therefore, we can observe that the welfare of successive northern generations declines constantly over time, characterizing intergenerational inequity as the younger generation is worse off than its parents.

Second, in the long run, we examine how an increase in the vulnerability of the South to climate change affects the stationary welfare of northern agents. We identify two channels: a terms of trade effect and a dynamic (in)efficiency effect. Both effects occur through the decrease in the world relative price of the green good driven by the increase in damages. On the one hand, movements in the world price modify the terms of trade. This change generates a positive or a negative impact on welfare in the North depending on its comparative advantage, which itself depends on the extent of the South's vulnerability. When this vulnerability is low, the North has a comparative advantage in the green sector. However, when this vulnerability is high, the relative capital abundance of the North becomes sufficiently high that it has a comparative advantage in the polluting - capital intensive - activities, despite its larger productivity in the green production. While the fall in the relative price of green to brown goods deteriorates the terms of trade of the North in the first case, it improves the terms of trade when the North is a net exporter of the polluting good. Thus, the terms of trade effect on northern agents' welfare is positive when the South's vulnerability is high, and negative otherwise. On the other hand, the dynamic (in)efficiency effect depends on the dynamic efficiency properties of the North; i.e., if northern agents under- or over-accumulate capital with respect to the socially optimal solution. As the vulnerability of the South decreases the relative price of the green - labor intensive - good, damages entail a negative income effect on northern workers which reduces their ability to accumulate capital. Therefore, this effect is positive on welfare when the North over-accumulates capital, while otherwise, it worsens under-accumulation and harms the welfare of agents.

The two effects of the South's vulnerability to climate change on northern agents' welfare can act either in the same or opposite directions. In the end, we show that the North region suffers from the higher damages abroad, as long as agents' preferences for present over future consumption are sufficiently high. Unlike Schenker (2013), we obtain this outcome even if there is an improvement in the North's terms of trade.

Overall, the international community has become increasingly aware of the importance of public interventions and international cooperation in preventing the welfare loss resulting from climate change. Our analysis reinforces this idea by showing that in a world with free trade, there can be strong economic incentives for countries - even if their exposure to the direct effects of climate change is low - to fight against this global phenomenon (i.e., invest in mitigation) and to provide assistance to countries that are more vulnerable to climate change (i.e., help them to adapt).

3.2. Public debt and the environment in an intentional context

In a second article, I focused on the interactions between public debt and global environmental problems in an international context. Environmental objectives are a particular concern for low-income countries in which these challenges are compounded by high levels of external economic vulnerability and public debt. They recurrently use public debt to absorb the impact of external macroeconomic shocks. In turn, higher levels of public debt associated with weak macroeconomic situation increase fiscal pressure and constrain the capacity of countries to address vulnerabilities and to mitigate pollution, notably through crowding-out effects that slow down capital accumulation.[14] The Covid-19 crisis as well as the increase in extreme weather events has further reduced the fiscal space of many governments by increasing the likelihood of sovereign debt stress. While many vulnerable countries were already characterized by lower access to global savings and/or higher financing costs, their rising debt levels appear to be an additional constraint on transition and adaptation financing. Besides, the importance of dealing with the debt profiles of countries to address environmental challenges has been emphasized by IPCC Working Group III and considered in dynamic models. A part of them considers debt policy to redistribute welfare gains from future to existing generations (see e.g., Bovenberg and Heijdra, 1998, Heijdra et al., 2006) while another part analyzes debt financing schemes for public and private mitigation (see Fodha and Seegmuller, 2012 and Fodha and Seegmuller, 2014). This literature, however, considers closed economies, which is a limitation as capital markets are interconnected and globalized, as climate and some global pollution issues.

In a paper co-authored with Mouez Fodha and Thomas Seegmuller entitled **"Pollution in a globalized world: Are debt transfers among countries a solution? published in the International Journal of Economic Theory in 2022 (Davin et al., 2021b)** we consider the economic and environmental effects of a debt transfer from rich to poor countries. When we examine the diversity of instruments used to provide climate finance, debt transfers, in the form of debt reliefs granted by developed countries to developing ones, currently represent only an insignificant proportion of financing strategies (0.3% according to Fenton et al., 2014). Yet, debt transfers are justified if they enhance the environmental quality and economic variables (consumption, savings, capital...) simultaneously. We examine if a debt transfer in favor of low-income countries is a relevant macroeconomic policy to promote pollution reduction. This question is of interest when international environmental policies have not been implemented to fight pollution effectively. Therefore, classical economic policies must regain legitimacy. This article contributes to this question by using a theoretical approach combining debt transfers and global pollution issues. We aim at analyzing the consequences of a debt transfer from high-income to low-income countries on pollution, GDP and well-being.

We develop a two-country model with global pollution externalities. Production deteriorates the environmental quality, harming the welfare of future generations, but public abatement which linearly increases with income improves it. Total-factor productivity determines the country profile: we define the low-income (resp. the high-income) country as

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[14] Collard et al. (2015) show empirically the extent to which debt levels can be a limit for financing future investments. They propose a measure of maximum sustainable government debt for advanced economies that strongly varies across countries.

the one with the lower (resp. the higher) level of productivity. According to the empirical evidence, people of the richest country are the more patient and hence have the highest saving rate. Countries are also characterized by different level of debts. Issuing public debt and tax on agents' income are used to finance public abatement and debt services. The overall debt remains constant, even after international debt transfers have taken place. This implies a constant global debt supply and rules out issues related to unsustainable global debt.

We study the environmental and economic consequences of a debt relief in favor of the low-income country, funded by the high-income country. Under perfect mobility of assets, the debt transfer implies a redistribution of income net of tax between the countries and modifies the debt burden and public abatement through a general equilibrium effect. When the interest rate is low, issuing more debt in the high-income country reduces taxation and increases savings. In this context, debt relief raises capital because this country has the highest saving rate and capital market integration is prefect. Environmental quality increases because public abatements per unit of income are assumed to be sufficiently efficient. A debt relief can therefore be beneficial for both capital accumulation and the environment, but also welfare, when the interest rate is low.

We then analyze the robustness of these results when the mobility of assets is imperfect. To that extent, we consider the polar case without mobility of capital. In this case, savings of each country should finance its own public debt. Since a debt relief means that public debt increases in the high-income country and decreases in the low-income country, there is a crowding-out effect on capital in the former country, whereas we observe exactly the opposite effect in the last one. Environmental quality still improves if the effect of public abatement net of pollution raises sufficiently in the low-income country, which happens if debt in this country is high enough. Therefore, the main difference between perfect mobility of assets and weak mobility concerns the real side of the economy. The question is whether debt emission in country with high income can be financed or not by over-saving of the other country. If it is mostly not the case, capital does not raise in the high-income country because of a crowding-out effect. Capital market integration is thus a key determining factor of the effect of the policy. This is in line with the result of Müller-Fürstenberger and Schumacher (2017) that propose a dynamic model where all agents contribute to a global externality, but only those in a specific region suffer from it. They show that if agents suffering from the externality are low-income, capital market integration may help to escape from an environmental poverty trap.

In this analysis, we have leaved aside the positive and significant effects of climate vulnerability on sovereign returns and thus the idea that there is a vicious circle in which vulnerability is self-perpetuating through the channel of public debt financing. This relevant aspect is discussed in the next section.

4. PROJECTS

The previously mentioned studies have been published. My research agenda is now driven by short and long-term projects. This section thus highlights two ongoing projects on topics that have not yet been explored in my published research. They concern the energy transition, a project developed with Francesco Ricci and in which Aurélien Lafrogne's thesis is embedded, and resource management, a subject investigated thanks to a grant received by the University of Montpelier in 2020. Then, my objective is also to use the knowledge gained from my previous studies to extend the topics I have already explored. Thus, I present two projects along the lines of works presented in Sections 2 and 3.2.

4.1. Energy transition and green finance

All economic activity requires energy. Currently, this energy is mostly obtained from the use of fossil fuels.[15] However, these sources of energy have negative impacts on the global climate change that we are already experiencing and whose damages will greatly worsen if the world greenhouse gases emissions stay on the same path (IPCC, 2022b). To limit global warming, a transition to alternative energy sources is broadly identified as necessary, being one of the main levers of climate change mitigation. A challenge therefore lies in identifying the means to make the production process greener and reach a sustainable development path. The challenge is huge as global energy sector CO2 emissions have continued to rise by 4.6% from 2015 to 2019 (IPCC, 2022b). At the EU level, the commission has proposed a 2030 climate target plan with the objective of reducing greenhouse gas emissions by at least 55% from 1990 levels by 2030. The International Renewable Energy Agency (IRENA) estimates that an average investment of 73 billion per year in renewable energy is needed to achieve this goal (IRENA, 2018). Public authorities play a central role in promoting investments in green capital, notably through incentive policies aimed at supporting the attractiveness of private investments in renewable energy. Private financing is indeed necessary for the transition to low-carbon energy. An analysis of the financing structures of the energy transition by IRENA shows that in 2019, 80% of total investments in the energy sector were private.

Two main families of public policies lever could be used for crowding in private investment in the green capital. First, instruments aiming at directly improving the competitiveness of low-carbon technologies relative to the carbon-intensive ones. They encompass most commonly discussed and implemented policies, such as carbon pricing or subsidizing purchases of energy produced from renewable sources (Stiglitz et al., 2017). For instance, carbon pricing increases the purchaser price of carbon-intensive energy, and to the extent that demand for energy is inelastic it allows otherwise more expensive energy sources to enter the market. In this case, the prospective return on investment in green capital is increased

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[15] Based on the International Energy Agency, in 2019, coal, oil and natural gas represented 80.9% of world total primary energy supply.

since ultimately energy expenditures by consumers increase. Nevertheless, the public and academic debate on climate policy has emphasized the need to complement carbon pricing with other environmental and energy policy instruments (Steckel and Jakob, 2018). This is particularly relevant as market failures in the process of credit creation and allocation by the financial system represent a serious impediment, in addition to the environmental externality (Campiglio, 2016). Thus, second measures that rely on the financial channel, and improve the conditions for accessing financing for investment in green capital relative to carbon intensive technologies are important. They are generally referred to as *green finance*.[16] The concept of green finance is a long-standing one promoted with the adoption of the Paris Climate Agreement in 2015, which refers to financial measures and instruments, such as green bonds, that promote the financing of the ecological transition. The idea behind these instruments is that they can be associated with a positive *greenium*, i.e. offering a lower return to investors and therefore a lower cost of capital for low-carbon activities. The stakes of green finance seem high, since low-carbon investment faces more sever credit constraints than carbon intensive project (Noailly and Smeets, 2021).

Green finance for the energy transition: Countering biases in the financial system

In the light of elements previously presented, the following relevant questions emerge. Why and how credit market imperfections could affect the transition to a low-carbon energy system transition? Can green finance tackle this issue and how does it interact with other climate policy instruments? In a work in progress with Aurélien Lafrogne and Francesco Ricci, we address these questions relying on a theoretical approach.[17]

We use a basic and tractable partial equilibrium model in which the is an asymmetry across the natural resources that are mobilized in the two alternative energy production processes. For simplicity, let us refer to the carbon and the green sectors. While the natural resources employed for the production of energy from renewable sources, such as wind or solar, are considered abundant and available at no cost, the fossil resources used in the carbon sector are typically produced and receive an income. Hence, we consider the case where when the carbon sector provides a sufficiently large share of energy services, the demand for fossil resources is so high that resource owners earn a Ricardian rent. Instead, there are no rents ever on the supply of wind and solar resources.[18] Beyond natural resource, energy

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[16] At this stage, we use the term green or environmental finance rather than climate finance, that refers only to finance whose aim at reducing net carbon emissions and/or enhance resilience to climate damage. While our discussions are primarily focused on the energy transition, our approach remains broad enough to take into account other environmental priorities such as water, air pollution or biodiversity.

[17] Currently, the work is entitled "Green finance for the energy transition: Countering biases in the financial system". It has been presented in 2022 in workshop (Long Run Dynamics Economics, Rouen), in conference (FAERE, Rouen) and in seminar (Séminaires d'économie TREE, Pau).

[18] Our stance should here be qualified to the extent that several low-carbon technologies rely on scarce natural resources that are sold at large profits by producers. This is the case notably of lithium, a major input to the production of batteries. Moreover, the location of wind and solar farms can also give rise to Ricardian rents. Nonetheless, we only need to assume a relative advantage for the brown sector, i.e a greater ability to use a collateral, which is in line with empirical evidences.

producers need to invest in capital. We consider market failure in the financial market, that results in limited access to credit and within sector spillovers. As a behavioral assumption, we consider that investors take their decisions at the sector level: although they are aware of the heterogeneity across firms within each sector, they compute average earning per sector. Much in the spirit of Matsuyama (2008) the constraint implies that the marginal active firm in the sector is able to borrow only a fraction of its expected revenues. The lower the fraction, the stronger is the credit constraint. Underlying this assumption are implicit problems arising from asymmetric information and divergent objectives, such as moral hazard and adverse selection, which provide rationales for credit rationing.

Credit constraint are assumed to can become relatively tighter for the low-carbon intensive sector. This case can emerge, because of an asymmetry across low and high-carbon intensive sectors: the latter can benefit of the value of proved reserves of fossil resources (captured by the Ricadian rent) to improve its credit access conditions, an opportunity the low-carbon intensive sector is precluded from. This assumption reflects established empirical evidence. Concerning imperfect credit access in the context on energy related activities, Gilje et al. (2020) study credit access for shale oil firms at the project level, and find that "high-leverage firms (dependent on asset-based loans) mitigate financing frictions that arise at debt renegotiations [...] by increasing collateral value". Typically, the bulk of tangible assets booked by firms in the oil & gas industry are related to concession contracts, while financial regulation requires them to disclose the value of their fossil reserves. Assets tangibility is a major determinant of the ability to borrow and thus of the leverage ratio (De Haas and Popov, 2019), which hint to potential asymmetric credit access conditions, favorable to the carbon intensive sector (Andersen, 2017). Papoutsi et al. (2021) suggest that firms in the carbon-intensive sectors –including oil and coal– are relatively more leveraged in part because they hold tangible assets that can serve as collateral. Focusing on European firms over the 1995-2009 period, Noailly and Smeets (2021) emphasize that firms specialized in renewable energy innovation are relatively more vulnerable to financial constraint than firms in fossil-fuel, because they are more sensitive to shocks in the supply of internal finance. The literature on stranded assets provides additional empirical grounding. This literature focuses on the economic consequences of stricter climate policies accruing from their impact on the valuation of fossil-related assets, such as in-ground reserves. Increased investors' expectations on the likelihood of the implementation of effective climate policies would reduce the market value of these reserves, weakening the financial position of firms having booked in their balance sheets. According to Atanasova and Schwartz (2019), capital markets recognize this potential loss. Bolton and Kacperczyk (2021) estimate significantly higher stock returns for companies with higher levels of carbon emissions, reflecting a transition risk premium, providing evidence that expectations of potential loss are priced.

Our analysis allows us to put forward an original mechanism by which green finance could trigger a discontinuous shift of the energy mix, from a carbon-intensive one to one largely based on low-carbon technologies. Formally, two equilibria can co-exist, one characterized by low and the other by high carbon intensity of the energy mix. The feedback mechanism underpinning the possible emergence of multiple equilibria in our framework is the following. When the carbon sector has a large share of the energy mix, demand for fossil resources is high, their ownership generates rents, these rents improve the access to the credit market for firms in the carbon sector, so they benefit of a less stringent credit constraint, which materializes into a competitive advantage, justifying its relatively large share of the energy market at equilibrium. Vice versa, for a small share of the energy services provided by the carbon sector, the demand for fossil resources is low, so that there are no rents associated to the resource ownership, hence firms from the two sectors face the same conditions for accessing credit, which results in a level playing field where the energy mix reflects the differences in costs for factors exclusively. We show that the occurrence of multiple equilibira depends on specific configurations of parameters, which require a sufficiently low greenium. Hence, in an economy initially at the high carbon intensive equilibrium, the development of green finance could force the economy to suddenly shift to the low carbon intensive equilibrium, as the greenium becomes high enough to rule out the former equilibrium. The development of green finance could therefore exert a structural effect durably favorable to the green sector. In addition, we can also underline that a tax aiming at reducing the value of the fossil-related assets can guarantee an energy mix less intensive in brown energy but only if it is accompanied by a sufficiency important greenium.

This first analysis is intended to be extended to a general equilibrium setting. The literature has largely illustrated how it is relevant to use dynamic general equilibrium analysis to study transformation of the energy sector and its long-term economic consequences. Notably, the growth theory with directed technological change, in a context with non-renewable resources, has underlined that green policies can support specialized investments for a transition to a cleaner economy (see e.g., Grimaud et al., 2011; Acemoglu et al., 2016). Nonetheless, in this literature, the interactions with the financial market and the role of green finance are not explored. A possible line of approach to introduce dynamic general equilibrium in our analysis would be to formalized the saving behaviors, by considering green and brown savers and an energy demand, arising from the final sector. Such formalization would allow to consider the capital market mechanisms and hence the potential interactions between credit constraint, investment and green preferences.

Green bond issuance and hedging effect against climate policy events

Since the past few years, policy engagement favoring global economy transitions away from fossil fuels to renewable energy has sharply increased. Countries that signed up to the Paris agreement in 2015 has committed to implement ambitious climate policy. For EU leaders, the road-map to endorse a binding EU target for a net domestic reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990 has be associated to “The European Green Deal" and to legislative proposals, contained in the “fit for 55" (FF55) package. Since the adoption of this package by the European Commission on July 14, 2021, a decision-making process has been engaged at the EU level in order to align current laws with the 2030 objectives.

In conjunction with this climate policy deployment, concerns about climate transition risk have emerged. Climate transition risk includes effects on firms' cash flows coming from a possible transition to a low-carbon economy. For listed firms, it refers to the fact that transition-related changes in official climate policy could lead to a repricing of financial assets. Transition risk presents a special concern for companies that rely more on carbon intensive production and consumption. Battiston et al. (2021) recently find that since the Paris agreement, firms with higher levels of carbon emissions have offered higher stock returns, illustrating the existence of a carbon premium related to long-term risks. While evidences suggest that green stocks better hedge climate risk than brown stocks (see e.g., Engle et al., 2020; Ardia et al., 2021; Pastor et al., 2021) this empirical question deserves additional studies, especially because it remains difficult to classified a firm as brown or green. Indeed, green taxonomy and classification tools helping investors make informed investment decisions on green economic activities is challenging. The EU taxonomy adopted in 2020 projects to tackle the challenge.[19] The general idea is that firms with economic activity aligned with the taxonomy will give information that they are working towards a low-carbon transition and resilience to climate change.

In the literature, a green firm is often characterized by low carbon emissions and/or by high environmental, social, and governance factors (ESG score). More recently, Flammer (2021) has identified green bonds as a financing instrument giving a credible signal on issuers' sustainability plans. A green bond is differentiated from a regular bond by its label. The International Capital Market Association's definition of a green bond is "Green bonds are any type of bond instrument where the proceeds will be exclusively applied to finance or re-finance, in part or in full, new and/or existing eligible Green Projects and which are aligned with the four core components of the Green Bond Principles."[20] It thus differs from a regular obligation by the nature of the project financed, that promotes progress on environmentally sustainable activities. Central banks acknowledged about the need for such instrument to facilitate the transition away from fossil fuels and limit the risk for the financial sector. Distinguish firms being green bonds issuers or not appears thus relevant to analyze transition risk. In addition, green bonds also appear to provide diversification and hedging opportunities against tail risks, like Covid crisis, for investors in traditional assets. This result is supported by recent analysis of Guo and Zhou (2021), Naeem et al. (2021) and Arif et al. (2022).

In a work in progress with Aurélien Lafrogne and Thi Hong Van Hoang[21], we aim to

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[19] see `https://ec.europa.eu/info/law/sustainable-finance-taxonomy-regulation-eu-2020-852/law-details_en` for details on EU taxonomy.

[20] `https://www.icmagroup.org/sustainable-finance/the-principles-guidelines-and-handbooks/green-bond-principles-gbp/`

[21] Currently, the work is entitled "Green bond issuance and hedging effect against climate policy events. An

examine if the green profile of a firm has a hedging effect on the short-term financial effects generated by an increase in transitional risk. More precisely, we aim to test the conjecture that the use of green bonds as a financing instrument by firms can affect the reaction to a climate policy event. Considering that the announcement of green bonds insurance provides information about the environmental ambition of the firm (Tang and Zhang, 2020, Flammer, 2021), we expect an under-performance for firms being not green bonds issuers compared to those issuing green bonds.

Our analysis is based on the European stock market which is characterized by a growing of green bonds issuers these recent years, as illustrated by Figure 2. While firms having already issued green bonds at the time of the Paris agreement were only 6, they were 81 in 2021. Moreover, the European Green Deal presented in December 2019 by the European commission illustrates a EU climate leadership on climate norms and green technology. As mentioned by the actual European Council President, Charles Michel, "We are in a climate emergency. As President of the European Council, I have a clear goal: to make Europe the first climate-neutral continent on the planet by 2050."[22]

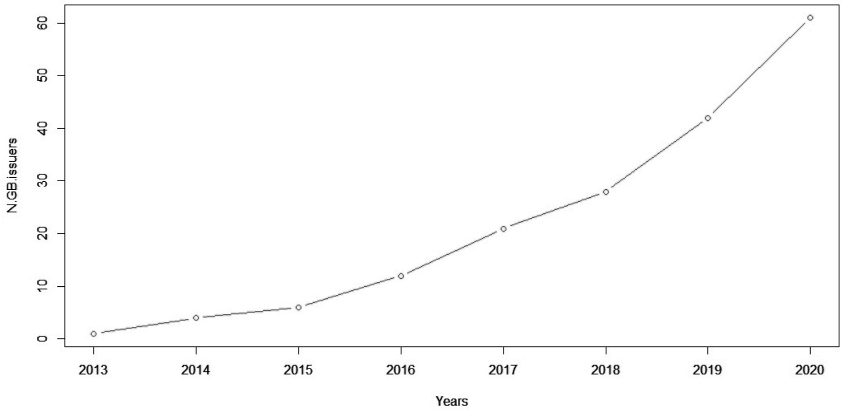

Figure 2: Evolution in the number of green bond issuers in the EUROSTOXX 600.
Source: data collected from the Bloomberg terminal

To examine if and how the issuance of green bonds by a firm modifies its stock market price reaction following policy announcement, we conduct an event study analysis for companies in STOXX Europe 600. We consider the presentation of the "fit for 55" (FF55) package by the European Commission as an event that capture important signal concerning european public engagement on climate actions. The package includes a set of connected and complementary proposals, including the reform of the EU Emissions Trading System, that aims at increasing carbon prices and thus incentives to reduce emissions. The package thus includes proposals to upgrade existing policy instruments but also to implement new ones. While the package can be viewed as welcome for firms with little carbon emissions,

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empirical analysis for European firms". It has been presented in 2022 at the FAERE conference in Rouen.

[22] https://www.consilium.europa.eu/en/eu-climate-change/

it will add substantial carbon costs for large carbon emitters. The reactions of the financial markets to this event, and in particular the distinct effect according to the green profiles of the company, have not been examined in the literature. There are several challenges to conduct an event study analysis with this policy event. First, define the event date, which is an important feature of the event study methodology. Indeed, as underlined by Binder (1985) “[] for many important regulations it is not accurately known when expectations change. [] regulatory events usually involve no single well-defined announcement; rather there are multiple announcements, such as committee, House, or Senate approval during the legislative or administrative process." The event "fit for 55" can be associated to several dates, we thus have to pay a particular attention to identify the date when investors became aware of the new information. Second, this event coincides with the Covid-19 pandemic and a shift in the monetary policy of the European central bank. Consequently, we pay a particular attention to identify potential confounded shock in the analyzed time period.

We start to investigate whether there are abnormal returns to the assets of companies in STOXX Europe 600. As the index is composed by firms having heterogeneous profile, and hence that some of them can react positively and the others negatively, we follow the approach of Ramelli et al. (2021) and we first conduct a descriptive between-group analysis by examining abnormal returns for several groups of firms. We examine the heterogeneous impacts by forming group based on greenhouse gas emission intensity and green bond profile. At the time of events examined in this paper, classification tools helping investors make informed investment decisions on green economic activities is not yet developed and greenhouse gas emissions is identified by the literature as relevant variable to capture climate risk exposure of a firm. We obtain that issuing green bonds help attenuate the impact of climate policy announcement on stock returns, while emission profile seems without consequence on firms’ reaction.

Then, we consider variability across firms to examine how the fact to have a part of debt financed by green bonds affects the reaction to the FF55 package. To this aim, we regress abnormal return on green bond issuer profile by controlling for characteristics that predict firms’ abnormal return and by using sector and country fixed effect. We obtain that the proportion of green bonds over the total assets of the firms has a significant effect on the reaction of stock prices whose sign is dependent of the leverage ratio of the firms.

Part of my short-term research program will be devoted to the completion and submission of these two works.

4.2. *Dynamics of common resource and experimental game*

In 2020, I was the principal investigator of the Support to Research at the University of Montpellier (SRUM) project "Dynamics of Natural Resources and Experimental Games" for an amount of 10500 euros. This project has consisted of laboratory experiments to study the problem of managing a renewable common resource in a dynamic context. Through this project I have developed collaboration with Dimitri Dubois, Katrin Erdlenbruch and Marc Willinger. This project has allowed to collect experimental data in order to address the topics specified below.

The consequences of climate disruption on the dynamics of the evolution of common pool resources are fueling issues around the management of the commons. Indeed, considering water resource for example, climate change is changing groundwater storage by raising the probability of severe drought occurrence or extreme weather events. Quality of the resource may be also affected as sea level rise may lead to salt water intrusion into coastal aquifers contaminating drinking water sources. This context recalls the importance of taking into account the dynamic character of resources. The theoretical framework associated with the problems of common pool management with dynamic resources and the predictions that follow from it, in terms of optimal trajectories and private behavior, are well established in the literature. The general framework is generally that of an optimization problem with a choice variable, the extraction of the resource, and a stock variable, the resource, whose evolution over time is governed by a dynamic law. There are few papers in the literature that adapt this type of program to an experimental game in the laboratory by taking into account the intertemporal dimension associated with the dynamic game. However, the experimental methodology, by providing a controlled environment, is particularly suited to assess individual behaviors in a dynamic context. The few contributions in the literature focus on identifying whether the agents are cooperative and on determining the type of behavioral strategies adopted by the agent with respect to the predictions of differential and dynamic game theory (Herr et al., 1997, Tasneem et al., 2017 and Djiguemde et al., 2022).

The project consists in two objectives. First, to make a methodological contribution as to the modeling of dynamic games in the laboratory. For this aim, we implement treatments to appreciate the divergences of behaviors in a dynamic resource extraction game when gains of the game are valued at the initial point in time or when they are valued at the current time of the experience. Second, we use the experimental framework to apprehend the reaction of agents to the possibility of a regime change in the dynamics of the resource. In both cases, the experiments is built to perform between groups analysis, comparing behaviors in the benchmark (control) case to those occurring in the treatments. The experiment consists of four parts, plus a socio-demographic questionnaire. In the first part, the subjects play the dynamic game alone (optimal control), they play the same game in pairs in the second part. Our protocol for the dynamical game is similar to the one of Djiguemde et al. (2019). Participants' task is to choose the level of extraction, which could be adjusted any time. They receive instantaneous feedback about the levels of the resource and their discounted payoff or gains. The third part aims at measuring the subject's impatience, with the Convex Time Budget method (Andreoni and Sprenger, 2012), and the fourth part the attitude towards risk with the Bomb Risk Elicitation Task (Crosetto and Filippin, 2013). Experiments was conducted in Montpellier (at LEEM) between January and December 2021 and we plan to program other sessions to extend our analysis to other contexts.

The first objective is to examine if the subject behaves differently when gains of the game are valued at the initial point in time or when they are valued at the current time of the experience. We base our work on a dynamic continuous time model of groundwater extraction, which can either represent the sole ownership case, as in Gisser and Sánchez (1980), or the competitive use of the resource by several players, as in Negri (1989) or Rubio and Casino (2001, 2003). These experiments rely on the predictions of standard dynamic extraction games with exponential discounting. Such models assume that players solve the dynamic extraction game at time $t = 0$ and therefore simply commit to their optimal extraction plan, without deviating from the conditional equilibrium path. However, in the experiments subjects are typically asked to update their extraction rate at each date t. In other words, in contrast to the underlying models where players are supposed to solve the game at time $t = 0$ and then automatically let it deploy, subjects involved in such experimental games have the possibility to constantly adjust their extraction rates. But, choosing an optimal path at the present time $t = p$ rather than at time $t = 0$, may affect players' perception of the game. Precisely, at time $t = p$ what matters for players, is the remaining optimal path for the remaining time, i.e. (p, ∞).[23]It is therefore important to know whether observed extraction paths in the laboratory differ or not, depending on whether discounted payoffs are framed as time $t = 0$ equivalents or as time $t = p$ equivalents. We thus implement two treatments: in the baseline treatment gains are measured in terms of time $t = 0$ equivalents while in the test treatment gains are measured in present time $t = p$ equivalents. The justification for the test treatment is that $t = p$ corresponds to the player's decision time.

The second objective is to use the experimental framework to apprehend the reaction of agents to the possibility of a regime change in the dynamics of the resource. Awareness is growing that many natural systems can undergo sudden and dramatic changes in their dynamics in response to a change in environmental conditions or in human activity. A central question is to know if the existence of a tipping point exacerbates the inefficiency associated to private exploitation of a common pool resource. In the presence of tipping points, the theoretical predictions concerning the trajectories of exploitation and evolution of the resource are mixed. It becomes optimal to increase or conversely reduce the exploitation of the resource compared to a setting without tipping points (see e.g., Tsur and Zemel, 1995, Ren and Polasky, 2014, de Frutos Cachorro et al., 2014). Theory also teaches that the inefficiency of welfare strategies will be accentuated or reduced by tipping points (Sakamoto, 2014, de Frutos Cachorro et al., 2019). These discrepancies in theoretical predictions about optimal and private responses depend on the nature of the shock, whether it is certain or not, but also on preferences for time or the discount rate. We conduct laboratory experiments to identify the behavioral consequences of deterministic shocks and to compare them to theoretical predictions. Works in experimental economics aiming at analyzing the effects

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[23] This issue was already discussed in Strotz (1956) who proposed two behavioral strategies that can guarantee coherence: precommitment and consistent planning.

of tipping points on the dynamics of a resource are scarce and do not rely on the theoretical foundations of dynamic optimization models (see Schill et al., 2015 and Lindahl et al., 2016). We examine two treatments, in addition to the baseline control in which there is no change in the dynamics of the resource. In the first treatment we consider a sudden change in the dynamics of the resource that occurs at a date which is known. Such a deterministic exogenous shock cannot be avoided and may occur due to a decrease in mean precipitation that leads to a decrease of the water availability for the users of the resource. The data collected will be used in part to test the theoretical predictions of de Frutos Cachorro et al. (2014). Second, we design a treatment to deal with the optimal management of a common pool resource with regime switching problems related to the notion of irreversibility. More precisely, we assume an ecological switch triggers by a threshold level defined on the state variable. In the experiment, when resource falls beyond a certain threshold value, extraction is no longer possible. Location of the threshold is assumed to be known. We can illustrate this issue by the exploitation of a coastal aquifer. Excessive extraction may lead to a decline in the groundwater, which may result in seawater intrusion what renders the aquifer useless (at least for a long time). This second treatment allows to consider an endogenous threat, as the regime shift is, at least partly, due to agents' extraction decisions. In that case, theory informs that it is optimal to avoid the occurrence of the event (Tsur and Zemel, 1995, Le Kama et al., 2014).

Part of my research program in the short run will therefore be dedicated to the processing and analysis of these data, to confront them with theoretical predictions. Moreover, we plan to use the experimental framework developed to relax the context of deterministic shocks. Indeed, the presence of irreversibly is particularly important under uncertainty. We thus plan to adopt the exogenous uncertainty definition of Tsur and Zemel (2004). We will assume that the current resource stock level can affect the hazard of immediate occurrence but whether the latter will actually take place will be determined by stochastic exogenous conditions. Reconsidering the groundwater example, saltwater intrusion can be due to anthropocentric but also to natural hazards because climate change impacts on this resource remains characterized by a high uncertainty. In a similar perspective, we will examine agents' behavior when there is a sudden change in the dynamics of the resource that occurs at a date which is unknown.

4.3. Environmental issues, inequality and health

Economic analysis of the link between air pollution and mortality give insights about how the level of income may affect the pollution-mortality outcome (see Arceo et al., 2016). We can highlight two main reasons. First, we can observe different levels of pollution exposure between rich and poor. From this channel, low-income population suffers more from pollution especially if there exists a non-linear dose relationship between pollution and mortality. Second, the costs of avoidance behavior generally differ considerably between the two contexts, in part because of a different access to health care or to quality housing stock for example, what makes the vulnerability to a given level of pollution different. Considering this second channel, higher income agent consumes more of health-related goods such as adequate food, medicine and health care while the marginal benefit of such spending is generally assumed to be more important for the poor. This means that to analyze health outcomes we need to consider not only income but also its distribution across population and hence inequality. This is support by empirical evidences focused on health and inequality that obtain that the effects of inequality remain substantial after controlling for median income levels. Hence, inequality has a unique effect on health distinct from individual income levels (see Payne et al., 2017).

In a project with Karine Constant and Emmanuelle Lavaine, I plan to extend the analysis developed in Section 2 to explore if and how the level of income inequality in a population can affect the health effect of pollution. This question deserves both empirical and theoretical contributions. We thus attempt to provide a contribution to the scare macroeconomic theoretical literature dealing with interaction between inequality and health when mortality is driven by pollution and health spending and to the emerging empirical literature that examines if the cost of pollution on mortality is higher in a state with high inequality.

The relationship between inequality and population health has been well documented in the empirical literature. On the one side, through the concept of income gradient in health, which refers to structural inequalities in health because of multiple individual differences between rich and poor (see e.g., Currie et al., 2020). On the other side, through analyses underlying that greater income inequality among population is associated with poorer population health (see e.g., Truesdale and Jencks, 2016). The specific effect of inequality on the interplay between health outcome and air pollution has received less attention and results are contrasted. Charafeddine and Boden (2008) find that agents report less a poor environmental health when the level of inequality is larger while Hill et al. (2019) show that particulate matter $PM_{2.5}$ is more harmful for average life expectancy in states where a higher percentage of income is concentrated in the top 10% of the state income distribution.

As regards theory, we are interested in examining interactions between economic, longevity, pollution and inequality and their long-term effects. There exist some macroeconomic models that deal with such interactions (see e.g., Constant, 2019). Nonetheless, in these models, individuals cannot directly influence their own life expectancy, meaning that the concavity effect of income does not directly determine average health outcome. Hence, the interplay between inequality and pollution-related adult mortality is not fully explored.

We will thus develop a model similar to Constant and Davin (2021) in which, in a context of health pollution issue, private health spending can be the source of inequality process. We will therefore focus on inequality in vulnerability to pollution, which can translate into health inequalities.[24] We will distinguish from this paper by focusing on mortality rather

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[24] We will leave aside principles of power, proximity, and physiology to explain the effect of inequality on health outcome. These principles are especially relevant when we compare mortality between states or coun-

than children health and by considering the interplay between public and private health spending in line with Bhattacharya and Qiao (2007) and Raffin and Seegmuller (2017). This interplay is important to understand the mechanisms linking inequality and health and their consequence for long-term relationship between health pollution and growth. With this model, we will examine if and why average mortality responds differently to pollution when the long term-state is characterized by inequality.

Then, we will conduct an empirical analysis for France for the years 2000 to 2015, where the average mortality in the theoretical model will be identified as the age-standardized mortality rate for a municipality. As a baseline, we will estimate a fixed effects model, that controls for time-invariant differences across locations and overall trends, to test the relationship between pollution exposure and mortality rate in a given municipality. To conduct this estimation, we have annual total mortality outcomes from the French epidemiology center on medical causes of death (CepiDC) and mean of pollution concentrations are drawn from a unique and detailed dataset compiled by the French National Institute for Industrial Environment and Risks (Ineris). An instrumental variables strategy based on meteorological factors will be used to avoid simultaneity problem. Then, we will turn our attention to the impacts of PM_{10} on mortality with respect to inequality indicators. We plan to use several inequality indicators per unit of consumption: interdecile gap, interquartile range, Gini and income share of the top 10%. Rich dataset will allow us to examine if the potential effect of inequality on mortality is not related to local factors but rather resides on individual factors within municipalities.

In a context in which heat waves are already becoming more common and intense in Europe, we also plan to extend our discussion around inequalities by considering temperature-related mortality. Keeping a macroeconomic perspective, this would notably imply to consider pollution not as a flow variable but as a stock in our theoretical analysis.

Part of my medium-term research program will be devoted to this project.

4.4. Global environmental issues and international perspectives

As mentioned in Section 3.2, when I present my work on the topics of public debt and environment in an international context, I have leaved aside the issue of debt sustainability. Nonetheless, the interactions between public debt and global environmental problems can refer to the positive and significant effects of climate vulnerability on sovereign yields (Buhr et al., 2018) and thus to the idea that there exists a vicious circle in which vulnerability is self-perpetuating through the channel of public debt financing. Considering this dimension seems essential to address climate change damages. In September 2022, among 67 low-income countries, the Debt Sustainability Analysis provided by the World Bank Group and the IMF [25], identified 32 countries with a high risk of overall debt distress and 8 countries

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tries that differ sufficiently in terms of political power and environmental commitment.

[25] see `https://www.worldbank.org/en/programs/debt-toolkit/dsa`

already in distress. This worrisome observation coupled with the increase in the frequency and intensity of extreme weather events (EWE), especially in these vulnerable countries, emphasized the urgent need to propose adapted policy tools to stop the vicious circle climate-debt vulnerability. It implies to measure and monitor the macroeconomic effects of EWE considering sovereign risk and to give insights into the transmission mechanisms between EWE and public debt. In this perspective, I am involved as a member in an ANR JCJC project submitted by Karine Constant in 2022 about the subject of vulnerability to extreme weather events and the role of public debt. I will contribute to this project through my theoretical background, developed in Constant and Davin (2019) and Davin et al. (2021b). We will examine how the mutual interactions between EWE and public debt may hinder economic growth and development, given their effects on debt sustainability and on the adaptive capacity of countries to climate change. Then, in line with Constant and Davin (2019), one objective would be to examine how the vulnerability of public debt to EWE may spread across countries, through international borrowing markets and through international trade.

5. CONCLUDING REMARKS

In my research, I have mainly adopted a macroeconomic perspective as I am interested in long-term sustainable growth. Some of my projects are currently designed with a microeconomics approach, and I consider them as important to enrich my macroeconomic approach which remains essential for evaluating economic and environmental policies. Indeed, neglecting the interactions between environmental policy and macroeconomic variables may lead to overlooking some important feedback effects in the economy. Macroeconomics is necessary to identify under what conditions environmental policies can be reconciled with the achievement of growth, development and inequality objectives.

The different projects presented in this thesis will define my future research trajectory. Even if each project has its own singularities, they have links between them. They are articulated around common themes and perspectives that I would like to highlight. In particular, my projects combine economics and the environment to address, directly or indirectly, the consequences of climate change. Moreover, all give perspectives to address the dynamics of inequalities related to climate problems.

Currently, I am treating the issue of environmental inequalities through the prism of local pollutants. My ambition is to continue to develop and enrich my research axis around the evolution of inequalities and their long-term economic implications by focusing on climate change related issues. My current projects are consistent with this objective. The design of climate policies to mitigate carbon emission and to adapt to a changing climate raises the question of inequalities between and within countries. Weather and climate conditions have a considerable influence on our living environment and our health. Climate change will aggravate existing health risks, and hence health inequalities, through several channels which can be considered in my projects. It will promote heat waves, the occurrence of vector-borne diseases, or food insecurity, notably through the problem of water supply management. My project on common pool resource dynamics will therefore be useful in adequately defining resource exploitation behaviors when resource dynamics may be affected by climate change.

Then, my works in progress around the topics of green finance allow to examine policy tools for energy transition. For now, I am focusing on mitigation finance as I am considering mainly investments to reduce global carbon emissions. The knowledge I have already acquired on this topic would be useful to address the consequences of environmental issues and hence to explore adaptation finance. Private investment in climate adaptation are indeed essential to define targeted actions on the most vulnerable populations and to reduce economic inequalities driven by global climate change. This issue will be explored in the project about extreme weather events and the economics.

6. CURICULUM VITAE

Marion Davin

Assistant professor in economics
Center for environmental economics - Montpellier

E-mail: marion.davin@umontpellier.fr
Web page: `https://sites.google.com/site/davinmarion/`
Adress: Faculté d'économie, Av. Raymond Dugrand, Site de Richter C.S. 79606.
34960 Montpellier Cedex 2
Civil Status: born Dec. 6th 1987, French, married, two children.

Research Fields

Main fields of interests: Macroeconomics, environmental economics.
Special concerns: International economics, growth, pollution, human capital.

Academic Position

Since 2015 : **Assistant Professor in Economics at CEE-M**, Université de Montpellier.
2014 - 2015: **Research and teaching Assistant**, IAE Université Lyon 3.
2013 - 2014: **Research and teaching Assistant**, Aix-Marseille Université.
April-June 2014: Visiting Student at Université de Laval (CIRPEE), Québec.
2010 - 2013: **Doctoral Grant and teaching Assistant**, French Ministry of Research, Aix-Marseille Université.

Education

2010-2014: PhD, in Economics, Aix-Marseille School of Economics - GREQAM - Aix-Marseille Université. Thesis: Essays on growth and human capital: an analysis of education policy, highest honors
PhD Supervisors: Karine Gente and Carine Nourry,
Jury: Andres Irmen (Referee), Katheline Schubert (Referee), Alain Venditti (Chairman)

Teaching

2015- Université Montpellier, Economics Faculty.

◇ Lectures, B.S. in economics: Macroeconomics, Principles of economics, Economic problems

◇ Lectures, Master. in economics: Macroeconomics, Economic development, Public economics and taxation, Globalisation international trade and the environment

2014-2015, Université Lyon 3, IAE Lyon School of Management.

◇ Lectures, B.S. in economics: Microeconomics (2^{nd} year), International Economics (3^{rd} year)

◇ Tutorials, B.S. in economics: Macroeconomics: Finance and Monetary Economics (1^{st} year), Microeconomics, (2^{nd} year), International Economics (3^{rd} year)

2010-2014, Aix-Marseille Université, Economics and Management Faculty.

◇ Tutorials, B.S. in economics: Mathematics (1^{st} and 2^{nd} year), Macroeconomics (2^{nd} year)

Supervision of students

Thesis (Co-supervisor 50%):

◇ 2020 Aurélien Lafrogne. "Le rôle de la finance verte dans la transition énergétique : une perspective macroéconomique"

Master:

◇ 2021. Makouma Bafaya Koukoura. "Évolution des inégalités départementales de santé en France".

◇ 2021. Massoade Isaac Bohi "Préférence pour l'environnement, croissance et commerce: Une étude empirique des déterminants macroéconomique de la protection environnementale."

◇ 2020 : Tahir Hisseine. "Analyse des déterminants de la consommation des ménages en France en contexte de crise."

◇ 2019 : Medoune Thiaw "Évolution des inégalités socio-économiques de mortalité en France: approche par commune et par classe d'âge."

Research articles published

◇ Pollution in a globalized world: Is debt transfer among countries a solution?, *with M. Fodha and T.Seegmuller*, International Journal of Economic Theory (2022).

◇ Environment, public debt and epidemics, *with M. Fodha and T.Seegmuller*, Journal of Public Economic Theory (2022).

◇ The Role Of Health At Birth And Parental Investment In Early Child Development. Evidence From The French ELFE Cohort, *with E.Lavaine*, Journal of European Health Economics (2021).

◇ Pollution, children's health and the evolution of human capital inequality, *with K. Constant*, Mathematical Social Sciences (2021).

◇ Unequal vulnerability to climate change and the transmission of adverse effects through international trade, *with K. Constant*, Environmental and Resource Economics (2019).

◇ How crucial are preferences for non-tradable goods and cross-country sectoral TFP gap for integration?, *with K. Gente and C. Nourry*, Journal of Macroeconomics (2018).

◇ Environmental policy and growth when environmental awareness is endogenous, *with K. Constant*, Macroeconomic Dynamics (2018).

◇ Should a country invest more in human or physical capital? A two-sector endogenous growth approach, *with K. Gente and C. Nourry*, Mathematical Social Sciences (2015).

◇ Public education spending, sectoral taxation and growth, Revue d'économie politique (2014).

◇ Social Optimum in an OLG model with paternalistic altruism, *with K. Gente and C. Nourry*, Economics Bulletin (2012).

Seminars and Conferences

◇ 2022. Workshop Epidemics, Ecology and Economy: intersections and interplays, *Bordeaux*; 7th Workshop Environmental and Resource Economics, *Montpellier*; Séminaire d'économie TREE, *Pau*; FAERE, *Rouen*; Workshop LOng-Run Dynamics in Economics, *Rouen*;

◇ 2021. EAERE, *Berlin, online*;

◇ 2019. Workshop in honor of Carine Nourry, *Marseille*; Environmental and resource economics seminar, CEE-M, *Montpellier*; 17th journée LAGV, *Aix-en-Provence*; Rencontre Sherbrook-Montpellier, *Sherbrook*;

◇ 2017. Environmental and resource economics seminar of EconomiX, Université Paris Nanterre, *Paris*; EAERE, *Athens*; 15th journée LAGV, *Aix-en-Provence*; Rencontre Sherbrook-Montpellier, *Montpellier*;

◇ 2016. FAERE, *Bordeaux*; IRMBAM IPAG, *Nice*; Environmental and resource economics seminar of LAMETA, *Montpellier*;

◇ 2015. Internal Seminar LAMETA, *Montpellier*; PET 15, *Luxembourg*; 14th journée LAGV, *Aix-en-Provence*; 19th T2M, *Berlin*; ADRES Doctoral Conference, *Paris*;

◇ 2014. ASSET Meeting, *Aix-en-Provence*; 63rd Meeting AFSE, *Lyon*; 18th T2M, *Lausanne*;

◇ 2013. PET 13, *Lisbon*; 12th journée LAGV, *Aix-en-Provence*;; 62nd Meeting AFSE, *Aix-en-Provence*; Instability and public policies in a globalized world : Conference in honor of Jean-Michel Grandmont, *Marseille*; PhD workshop AMSE, *Aix-en-Provence*; Overlapping Generations Days, *Clermont Ferrand*; 17th T2M, *Lyon*;

◇ 2012. 11th journée LAGV, *Marseille*; Overlapping Generations Days, *Marseille*;

◇ 2011. New Challenges for Macroeconomic Regulation: Financial Crisis, Stabilization Policy and Sustainable Development, GREQAM, *Marseille*; Overlapping Generations Days, *Vilesalm*; 15th T2M, *Montréal*;

◇ 2010. PhD student seminar GREQAM, *Marseille*.

Referral activities

Review of Economic Dynamics, Resource and Energy Economics, Environmental and Resource Economics, Macroeconomic Dynamics, Bulletin of Economic Research, International Journal of Economic Theory, Economics Bulletin.

Grants

2016-2021 : Member of the project ANR GREEN-Econ, supervised by Nicolas Quérou and Hubert Stahn.

2020: Head of the project SRUM (Soutien à la Recherche de l'Université de Montpellier) "Dynamics of natural resource and experimental games".

Administrative and Scientific Responsibilities

Since 2022: Co-supervisor of the Master Economy, Université de Montpellier.

Since 2018: Member of the economic faculty council of Université de Montpellier.
Since 2018: Group leader of the CEE-M research group "Preserving natural resources and biodiversity".
2022: Member of Jury of FAERE Young Economist Award Settlement.
2022: Member of the recruitment committee of assistant professors, AMSE, Université Aix-Marseille.
2020: Member of the recruitment committee of assistant professors, ERUDITE, Université Paris Créteil.
2019: Member of the recruitment committee of assistant professors, CEE-M, Université de Montpellier.
2017-2019: Alternate member of section 5 of the Conseil National des Universités.

Skills

Languages: French (native), English
Computer skills: Stata, Maple, Mathematica, Latex, MS Office, VBA

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ORIGINAL PAPER

The role of health at birth and parental investment in early child development: evidence from the French ELFE cohort

Marion Davin[1,2] · **Emmanuelle Lavaine**[1]

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Abstract

This paper combines a theoretical and an empirical approach to address how health at birth affects child development. Using a simple theoretical model in which parents invest in their children, we identify the mechanisms through which better health at birth can improve child development. We also emphasise how parental socioeconomic status can shape the effects of health at birth. We perform an empirical analysis on a French cohort of children born in 2011, using a unique dataset ELFE. We identify the effect of birth weight and gestational age on child development at 1 year. The results indicate that only gestational age positively affects early development. We find no empirical evidence for the existence of a severity effect, according to which the adverse effects of poor health at birth are higher for children in low-income families or with poorly educated mothers.

Keywords Early child development · Health at birth · Parental investment

JEL Classification C26 · I14 · I18

Introduction

It is well documented in the economic literature that investment in early childhood is the most powerful investment a country can make, given its long-term economic return and its opportunity to improve the distribution of human capital among agents.[1] The identification of human capital determinants remains a desirable proposition in the economic literature. Indeed, human capital plays a vital role in an individual's income potential and, as emphasised by Manuelli and Seshadri [36], plays a central role in determining the wealth of nations and their level of development.[2] Early child

The ELFE survey is a joint project between the French Institute for Demographic Studies (INED) and the National Institute of Health and Medical Research (INSERM), in partnership with the French blood transfusion service (Etablissement français du sang, EFS), Santé publique France, the National Institute for Statistics and Economic Studies (INSEE), the Direction générale de la santé (DGS, part of the Ministry of Health and Social Affairs), the Direction générale de la prévention des risques (DGPR, Ministry for the Environment), the Direction de la recherche, des études, de lévaluation et des statistiques (DREES, Ministry of Health and Social Affairs), the Département des études, de la prospective et des statistiques (DEPS, Ministry of Culture), and the Caisse nationale des allocations familiales (CNAF), with the support of the Ministry of Higher Education and Research and the Institut national de la jeunesse et de léducation populaire (INJEP). Via the RECONAI platform, it receives a government grant managed by the National Research Agency under the Investissements d'avenir" programme (ANR-11-EQPX-0038).

✉ Emmanuelle Lavaine
emmanuelle.lavaine@umontpellier.fr

Marion Davin
marion.davin@umontpellier.fr

[1] CEE-M, Univ. Montpellier, CNRS, INRAE, SupAgro, Montpellier, France

[2] CEE-M, Univ. Montpellier, CNRS, INRAE, SupAgro, Montpellier, France

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[1] Currie and Almond [19] provide a survey of empirical works that emphasise the long-term consequences for human capital of events occurring before age 5. The concept of dynamics complementarity presented in Cunha and Heckman [15], according to which the return on investment during childhood increases with early child development, provides an explanation.

[2] The Manuelli and Seshradi' paper attempted to explain the income differences between countries. They focussed on the human capital in each country and provided a new way to measure it. They found that cross-country differences in average human capital per worker were much larger than that suggested by previous studies. They concluded that a large part of the cross-country differences in wealth could be explained by differences in human capital quality.

development is a priority of WHO and UNICEF's work. The Commission on the first 1000 days of the child, launched in September 2019 by the French President, illustrates the importance of recognising the determinants of early child development in the design of efficient policy tools. This will lead to a better understanding of the mechanisms through which inequalities may be formed at an early age.

In this study, we focussed on health at birth as a determinant of early childhood development. The economic mechanisms linking these two elements and how the relationship between health at birth and early childhood development may differ between low- and high-income groups are not well documented in the literature. No data on France's situation are available due to the lack of large-scale studies. Data from the recent French Longitudinal Study of Children, ELFE—a rich cohort data set of children born in 2011 in France— fill the literature gap. We examined how health at birth affects French children's cognitive development at a very early age and how this effect differs between socioeconomic groups. We addressed this question by adopting an economic approach. More specifically, we adopted a theoretical and empirical approach to identify the impact of birth weight and gestational age on child development at the age of 1 year. In particular, we considered optimising parents' behaviours to theoretically assess the effect of health at birth on child development and to examine how a family's socioeconomic status can influence the relationship. We also considered a non-random assignment of health at birth when conducting the empirical analysis.

From an empirical point of view, the positive correlation between health at birth and child development is well documented (see, e.g., [35]). Moreover, the literature provides strong evidence that poor initial health negatively impacts the first few years of elementary school [27], reduces academic outcomes from childhood to early adolescence [5], and negatively affects adult health and skills development outcomes [1, 2]. Some authors also used rich cohort data sets to examine the effects of health at birth on child development. For example, Jefferis et al. [34] emphasised the negative effect of low birth weight on cognitive development at different ages in the UK. The authors, however, did not examine the different economic mechanisms that may link health at birth and child development. In the literature, evidence for very early childhood is scarce. Hence, we have little information on the potential effects of policy interventions in ameliorating this disadvantage during early life, especially in France.[3]

The literature on child development reveals that childhood's socioeconomic environment is crucial. In particular, it appears that the income gap in households with children translates into relative disadvantage early in life by affecting child development before age 5 (see, e.g., [2], who provide an explanation on how human capital develops during the early years.) Focussing on the interplay between health and family environment, part of the literature attempts to examine if poor health conditions affect children's development differentially across socioeconomic groups. There is no clear consensus emerging from the studies. Case et al. [9] examined health outcomes in the US and found that the negative health impact of chronic health conditions in early life is more pronounced in low-income families. In contrast, Currie and Stabile [21] found that the effect of a health shock on Canadian children's test scores and future health does not differ across socioeconomic groups. A recent study of Wei and Feeny [45] confirmed this result. Authors found no evidence that Canadian children from low-income families suffered more from poor health at birth than those of high-income families. In the UK, no evidence was found that social background modified the effect of birth weight on cognitive development Jefferis et al. [34].[4] While these studies did not provide a clear theoretical foundation to explain the economic intuition behind their results, we used theory to identify the mechanisms behind such interactions and appreciate how poor health at birth can inhibit skill formation.

Our contribution consists of two related parts to identify various channels that can explain the effect of health at birth on child development and to examine if and how health endowment and parental socioeconomic conditions interact to form child human capital.

We first developed a simple theoretical model based on parental investment in children, in line with the models of human capital formation proposed by Cunha et al. [16]. More specifically, based on an economic approach, we considered the crucial role of parental engagement with the child. Parents being rational and aware that they can affect their children's development invest a part of their time and financial resources. Returns on this investment depend on parental socioeconomic status and the health status of their children. In this way, the child's endowment affects the behavioural responses of parents. Thus, considering optimising parents' behaviours in the form of time spent with children, health at birth affects human capital through two channels. On one hand, health at birth can affect children's development directly through a purely biological effect that increases the risk of learning disabilities, academic difficulties, or behavioural problems. On the other hand, parents' engagement in children's development depends on their birth endowment. This

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[3] Wehby et al. [44] considered very early child development, between 3 and 24 months, but they focussed on parental and household investment effects, not on health conditions at birth. They performed an empirical analysis with South American participants.

[4] Not that it is difficult to give an indisputable explanation for the differences observed across countries as outcomes, explanatory variables, and the periods analysed differ in each study. Nevertheless, their results may suggest less equitable access to child health care in the US.

indirect effect of health at birth on child human capital can be positive or negative, depending on how child human capital is formed. We assumed a general formalisation in the theoretical part to discuss the different possible cases and to identify the global effect of child's birth endowment. We predicted that positive health conditions at birth would improve early child development and that parental behaviours can mitigate or amplify this relationship. Concerning the influence of a family's environment on the adverse effect of poor health endowments at birth, we concluded that affluent families suffer less when birth endowments and family's wealth (in the form of income and education) are substitutes to form early childhood human capital.

We then conducted an empirical analysis to test our prediction for France, using a unique dataset on the ELFE cohort's entire French territory. We aimed at empirically analysing the consequences of gestational age and birth weight on child development measured at 1 year. Moreover, we aimed to shed light on differential impacts according to the income and education of the mother. There are several empirical challenges in estimating health's causal effect at birth on child development outcomes. In particular, some omitted variables may be influencing both exposure and outcome. In our analysis, health at birth may be correlated with other factors, such as wealth, which may also be correlated with child development, generating a potential omitted variable bias problem [41]. Therefore, a naive ordinary least squares (OLS) analysis may overestimate health's actual effect.

To mitigate such issues and to infer the impact of health at birth on child development, we first used a rich set of sociodemographic control variables available in the ELFE database. Then, in line with the literature that reports seasonality in the birth outcome, we used the season of birth as an instrumental approach. The intuition to use season of birth as an instrument relies on the fact that it induces seasonal differences in maternal exposure to viral infections, meteorological factors, air pollution, food supply, physical activities, or diet, that directly affects health at birth, independently of parental characteristics (see, e.g., [42], forarecentreviewoftheepidemiologicalevidenceonseasonalityofbirthoutcomes). In this vein, Currie and Schwandt [20] underlined that higher influenza prevalence in January and February explains an increase in prematurity of more than 10% during these months.[5]

We first examined the relationship between health at birth and child development. To dissociate the parental investment effect from the biological impact identified in the theoretical part, we then questioned whether parental time investment is related to health at birth. From our results, we identified an effect of gestational age on early child development, mainly due to biological effect. Indeed, our results suggest that parental behaviour does not depend significantly on a child's health at birth. Birth weight is not a relevant determinant of child development in our study, in line with the analysis of Conti et al. [14], which underlines that birth weight is not informative as it can capture negative and positive aspects of foetal health.

We cannot conclude that there are inequalities in the impact of health at birth on child development, as we found no significant difference depending on the parents' revenue or education profiles of the mother. From our results, there is no evidence that lower family income exacerbates the incidence poor health conditions. Based on our theoretical prediction, this result means that health at birth and parental inputs are not complementary nor substitute to form early childhood human capital.

The rest of the paper is organised as follows. Section Theoretical framework presents a simple theoretical model of human capital formation. Section Data and empirical strategy is devoted to presenting the data and the empirical strategy. The results are discussed in Sect. Results. The last section is the Conclusion.

Theoretical framework

This section develops a theoretical model to highlight the link between birth endowment and human capital.

Setting

The concept of human capital refers to individuals' knowledge, skills, and health in different age groups. Thus, it can be cognitive and non-cognitive child development at each age. Following Cunha and Heckman [15], we considered this general definition for our theoretical discussion.

Our first objective in this section is to identify economic mechanisms explaining how and why children's health status, which defines their birth endowment, affects early child outcomes. We paid particular attention to the child's socioeconomic environment in examining this relationship. The idea that health at birth and interventions can affect future health and human capital are well established. However, as recently underlined by Bharadwaj et al. [5], parents' role in understanding the interplay between a child's endowment and human capital formation is crucial and not well studied.[6]

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[5] As the authors conducted their analysis using siblings conceived by the same mother at different times, differences in maternal characteristics as an explanation for seasonal differences in health at birth were excluded.

[6] The role of parents in this interplay is varied. For example, as revealed by O'Neill et al. [38], early public interventions aimed at supporting parents to address the child's behavioural problems may favour economic returns in the long term.

We provide a benchmark to describe the process of human capital formation during the early life by considering parental investment. Following recent literature that underlines the importance of investment in time during early childhood (see [29] for a review of the literature on child development and parental investment), we considered parental time input in line with Becker citeB65.[7]

Our study population is composed of households that consist of adults and their children. There are two types of parents $i = l, h$, differentiated by their skills or income W_i, which is the wage that they can obtain in the labour market.

Only parents make decisions. They possess one unit of time which can be partially e_i invested to take care of their child (families pre-school-age investments), while the remaining of time is allocated to work and earn the wage W_i. Parents use their income to consume c_i, such that their budget constraint is given by

$$(1 - e_i)W_i = c_i.$$

Children are characterised by their health endowment at birth H_i, and we do not consider the effect of parental characteristics on this endowment. Our objective is not to examine socioeconomic inequalities in health at birth and their consequences but rather to identify how parental wealth can affect the sensitivity of human capital formation to a given birth endowment.

Human capital formation refers to how a child's human capital is produced. In theory, child human capital formation occurs mainly in two distinct stages: during early childhood and the schooling process. In utero experience also affects the formation of human capital, but, as previously mentioned, in this study, we did not examine health inequality at birth. The formalisation proposed in the literature assumes that human capital at each stage is a function of parental investments, initial endowments, the stock of skills of the previous stage, and parental characteristics (see, e.g., [16]). For the sake of simplicity, we adapted this formalisation, and assumed a one-period model of childhood. This means that inputs at any of the stages of childhood are perfect substitutes.[8]

In our model, human capital is developed by formal investment made by parents. Formal investment refers to parents' level of wealth, the transmission of cognitive and social knowledge within the family, and by child endowment in health. The literature provides evidence that health at birth affects human capital, by its effects on education performance [5, 27] or on children's mental health [18]. Early childhood human capital is assumed to depend positively on three inputs: health endowment at birth H_i, a composite of the investment in time made by parents towards child care e_i, and parent's level of wealth W_i. We followed Cunha and Heckman [15] assuming a CES development technology to combine these inputs. Child development CD_i is thus governed by

$$\mathrm{CD}_i = \left(\lambda_1 e_i^{\frac{\sigma-1}{\sigma}} + \lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_3 W_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}; \quad \sigma > 0 \tag{1}$$

with σ capturing the degree of substitutability between the inputs. For $\sigma < 1$, health endowment and investment are complements, while for $\sigma > 1$, they are substitutes. The parameters $\lambda_1, \lambda_2, \lambda_3$ satisfy $\in \mathrm{IR}^{+}$.

From Eq. 1, we see the importance of health endowment at birth in the formation of human capital. Indeed, identifying health condition as an input of early child development implies that a better health condition increases the return to childhood investment, i.e., $\frac{\partial^2 \mathrm{CD}_i}{\partial e_i \partial H_i} > 0$.

Parents i derive utility from their consumption c_i and from their child's development CD_i. We assumed a Cobb–Douglas utility function, such that the parents' choice consists in maximising the following program:

$$\begin{aligned} &\max_{c_i, e_i} \ln c_i + \gamma \ln \mathrm{CD}_i; \quad 0 < \gamma < 1 \\ \text{s.t } & W_i(1 - e_i) = c_i. \\ & \mathrm{CD}_i = \left(\lambda_1 e_i^{\frac{\sigma-1}{\sigma}} + \lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_3 W_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}. \end{aligned} \tag{2}$$

Our objective is to determine how health at birth affects child development at the equilibrium, meaning when we consider behavioural responses of parents.

Interaction between child's health endowment and human capital

From program 2, the optimal investment e_i satisfies the following equality:

$$\lambda_1 e_i + \left(\lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_3 W_i^{\frac{\sigma-1}{\sigma}}\right) e_i^{1/\sigma} = \lambda_1 \gamma (1 - e_i) \quad \Rightarrow \quad e_i \equiv e(H_i, W_i). \tag{3}$$

The overall amount of parental resources spent on children stems from altruistic motives, captured by γ, and depends on parental income W_i if it is complementary or a substitute for other inputs ($\sigma \neq 1$). Otherwise ($\sigma = 1$), parental income does not affect parental investment. A higher level of wealth generates an income effect, that favours investment in children, and a substitution effect, that makes other investments more profitable. Both effects exactly compensate in our setting when $\sigma = 1$ because of the Cobb Douglas utility function.

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[7] Our general theoretical predictions hold if we assumed that parents directly invest an amount of wage rather than a unit of time.

[8] Having a one-period model of childhood, we did not distinguish between early investment and late investment, and hence, we did not consider dynamic complementarity. This is relevant as our focus is not on the life-cycle profile of investment.

Using Eqs. 1 and 3, we got the equilibrium value for the child human capital and obtained the following result:

Proposition 1

1. *Our model predicts that health at birth affects child development through a direct positive effect* $\left(\frac{\partial \mathrm{CD}_i}{\partial H_i}\right)$ *and through an indirect effect* $\left(\frac{\partial \mathrm{CD}_i}{\partial e_i} \times \frac{\partial e_i}{\partial H_i}\right)$, *which is negative* (*resp. positive*) *when inputs are substitutes* (*resp. complements*).
2. *The global effect of health at birth is positive*

$$\frac{d\mathrm{CD}_i}{dH_i} = \underbrace{\frac{\partial \mathrm{CD}_i}{\partial H_i}}_{\text{direct effect}} + \underbrace{\frac{\partial \mathrm{CD}_i}{\partial e_i} \times \frac{\partial e_i}{\partial H_i}}_{\text{indirect effect}} > 0. \tag{4}$$

3. *The return of a better health status at birth on child development depends on family's characteristics when* $\lambda_3 > 0$ *and* $\sigma \neq 1$. *More precisely, child development is less* (*resp. more*) *sensitive to health at birth for rich families when inputs are substitutes* (*resp. complements*)

$$\frac{\partial \varepsilon_{\mathrm{CD}_i/H_i}}{\partial W_i} \neq 0$$

with $\varepsilon_{\mathrm{CD}_i/H_i}$, the elasticity of child development to health at birth

$$\varepsilon_{\mathrm{CD}_i/H_i} = \frac{\lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_1 e_i^{\frac{-1}{\sigma}} \frac{\partial e_i}{\partial H_i} H_i}{\lambda_1 e_i^{\frac{\sigma-1}{\sigma}} + \lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_3 W_i^{\frac{\sigma-1}{\sigma}}}. \tag{5}$$

Our simple model shows that health at birth affects the child through two channels. A direct positive effect that can be viewed as purely biological and an indirect, positive or negative, that goes through parental investment. Investment can increase or decrease with H_i depending on how the variables that form human capital interact with each other. To evaluate the global effect of health at birth on child development, we decomposed the two effects in Eq. (4). From (1), we got

$$\frac{\partial \mathrm{CD}_i}{\partial H_i} = \lambda_2 H_i^{\frac{-1}{\sigma}} \left(\lambda_1 e_i^{\frac{\sigma-1}{\sigma}} + \lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_3 W_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{1}{\sigma-1}}.$$

Using (1) and (3), we got

$$\frac{\partial e_i}{\partial H_i} = \frac{e_i^{\frac{1}{\sigma}} \left(\frac{1-\sigma}{\sigma}\right) \lambda_2 H_i^{\frac{-1}{\sigma}}}{\frac{1}{\sigma}\left(\lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_3 W_i^{\frac{\sigma-1}{\sigma}} \right) e_i^{(1-\sigma)/\sigma} + \lambda_1(1+\gamma)} \times \lambda_1 e_i^{\frac{-1}{\sigma}} \left(\lambda_1 e_i^{\frac{\sigma-1}{\sigma}} + \lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_3 W_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{1}{\sigma-1}}.$$

By combining these two expressions, the global effect is driven by the sign of

$$1 + \frac{1-\sigma}{\sigma} \frac{\lambda_1}{\frac{1}{\sigma}\left(\lambda_2 H_i^{\frac{\sigma-1}{\sigma}} + \lambda_3 W_i^{\frac{\sigma-1}{\sigma}} \right) e_i^{(1-\sigma)/\sigma} + \lambda_1(1+\gamma)},$$

which is always positive, meaning that the indirect effect does not undertake the direct one.

Another approach is to ask whether the effects of health endowment are heterogeneous. We aimed to determine if the return of better health status on child development is higher for children with a good socioeconomic environment (i.e., a higher W_i). To achieve this goal, we examined how child development's elasticity to health endowment $\varepsilon_{\mathrm{CD}_i/H_i}$ changes with W_i. As presented in Proposition 1, this elasticity can differ among households when $\lambda_3 > 0$ and $\sigma \neq 0$. When these two conditions are satisfied, parental characteristics W_i affect elasticity directly and indirectly by modifying the way health endowment affects parents' investment $\left(\frac{\partial^2 e_i}{\partial H_i \partial W_i}\right)$. Both effects depend on input characteristics. When they are complementary ($\sigma > 1$), rich families suffer more from adverse birth outcomes $\left(\frac{\partial \varepsilon_{\mathrm{CD}_i/H_i}}{\partial W_i} < 0\right)$, while poor families suffer more when inputs are substitutes ($\sigma < 1$ $\frac{\partial \varepsilon_{\mathrm{CD}_i/H_i}}{\partial W_i} > 0$). Parental wealth is not a direct argument for the child development formation ($\lambda_3 = 0$), or where inputs are not substitutes or complements ($\sigma = 1$), there is no inequality. The return of better health at birth on child development does not differ among socioeconomic profiles.

Our theoretical results serve to motivate and interpret the observational work that is discussed below. Our aim is not to estimate the theoretical parameters of the human capital function nor to provide an estimated value for human capital. Rather, we examined if our theoretical predictions align with what we observed and concluded using the data. We would finally be allowed to deduce some properties regarding how inputs variables interact to form human capital.

Data and empirical strategy

Data and summary statistics

Health and child human capital outcomes are drawn from a unique and detailed dataset—ELFE—compiled by epidemiologists for the whole of France. ELFE is the first national birth cohort study in France. The ELFE project is a 20-year study of a cohort of 18,300 children recruited in 2011. The purpose is to gain a better understanding of how perinatal conditions and the various aspects of the environment affect children's development, health, and socialisation from the foetal stage to adolescence (see [10], for details about the cohort profile of ELFE). The data we used in the study included more than 13,235 children from the ELFE cohort interviewed in four waves in 22 regions[9] The wave represents babies born during four specific periods representing each of the four seasons in 2011: 1–4 April, 27 June–4 July, 27 September–4 October, and 28 November–5 December.

We used key variables of the ELFE dataset in our analysis. They covered the data at children's birth in 2011 and 1 year after birth in 2012. Table 1 presents the summary statistics of these variables. Our study focusses on cognitive development at age 1 to define the output, and on health at birth, birth weight and gestational age, to define childbirth endowment.

Figure 1 shows the distribution of birth weight as well as the distribution of gestational age.

The distribution of birth weight and the distribution of gestational age are approximately normal which justifies our empirical estimation in the next section.

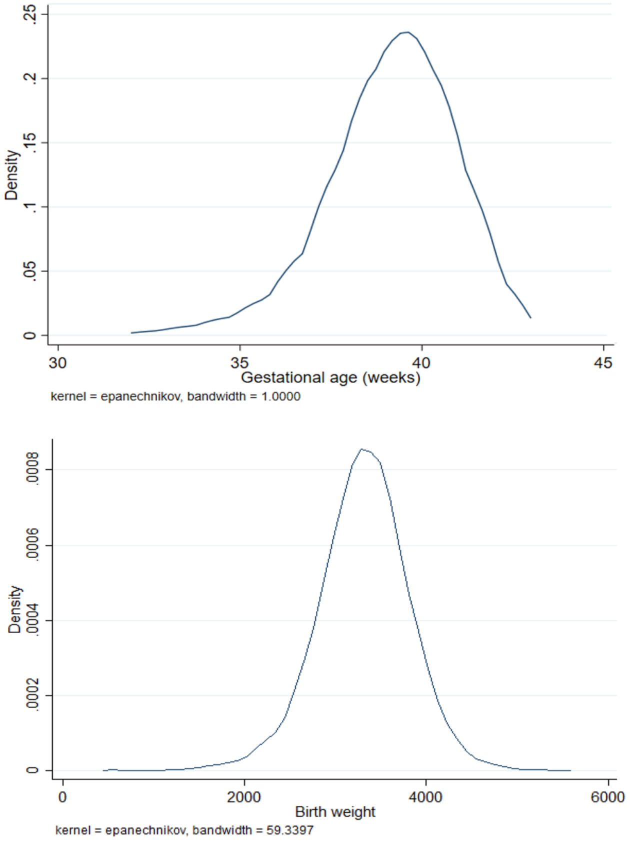

Fig. 1 Gestational age and birth weight distribution This figure shows the distribution of birth weight and gestational age using Kernel density estimate

The ELFE cohort allows us to define a relevant measure for capturing early childhood development when the child is 1 year of age. The cohort provides several variables related to the cognitive performance of the children. They derive from several questions that come from the French version of the "Child Development Inventory" developed by Duyme and Capron [26] and based on the methodology provided by Ireton [33]. After extensive research over 20 years, Ireton [33] developed a standardised parent questionnaire to assess the development of infants in their first 18 months. As reported by Glascoe and Dworkin [30], parent report measures, such as the "Child Development Inventory," successfully identified children with developmental and behavioural problems. We thus defined a general Child Development Inventory Index (CD) and also a six scale index that measures areas of development and learning. They include Social, Self Help, Gross Motor, Fine Motor, Expressive Language, and Language Comprehension scales. These indices can be accepted as a measure of human capital at 1 year. A large body of literature has identified health (measured at a particular age in childhood or at birth) as a form of human capital. The literature review provided by Becker [4] highlights the insights behind this relationship.

In child development questions reported in the ELFE cohort, respondents answered with "yes" or "no" to each question.[10] To construct a proxy for child development, we developed an index that corresponds to the percentage of positive responses

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[9] There are several reasons why we do not have 18,300 children in this database. All families whose mothers had given their consent for their children's follow-up in the maternity wards were eligible for the 1-year survey. However, not all mothers responded to the 1-year survey which led to a loss of many observations as we end up with 14 076. There are some missing observations as well. For example, the Child Development Inventory Index (CD) contains fewer than 14,000 observations, because we did not consider the absence of answers to the questions asked. However, the Pearson correlation coefficient between revenue and non-responses to the CD questions is very low, suggesting that non-responses do not bias our estimates.

[10] We did not consider the ones who do not respond to the questions. They are considered as "." in the analysis.

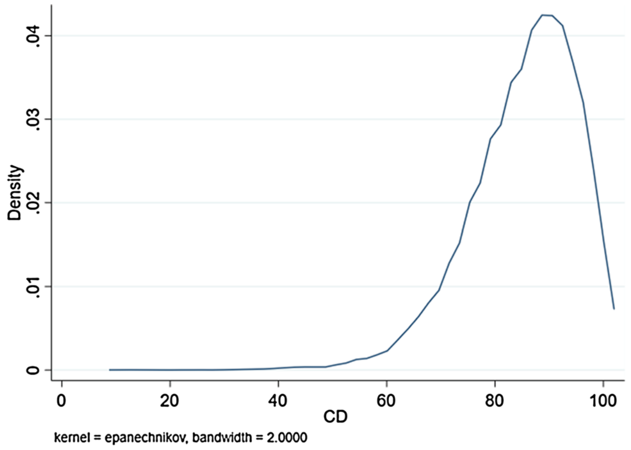

Fig. 2 CD distribution. This figure shows the distribution of CD using Kernel density estimate. A detailed description of CD can be found in the Appendix(table 6)

to questions. The list of questions used to build the CD and the six scales are provided in Appendix Sect. Child development.[11]

Figure 2 shows the distribution of CD. Unsurprisingly, most of the respondents respond positively to the questions.

The literature argues that the time parents spend with their children plays a critical role in health [40]. Parent–child time can be seen as a form of human capital investment that plays a vital role during early life. The link between parental time and early childhood development is poorly documented in the empirical literature [44]. Parental time investments in children have been considered as an input in child outcomes [22]. Del Boca et al. [23] and more recently Bharadwaj et al. [5] made significant contributions in this regard. Still, they did not evaluate the effects of parental investments in very early life stages. In this vein, we constructed an index that considers the time parents spend with their own children. To do so, we used several ELFE variables. The 1-year interview includes several questions about activities parents do with their children (small games, reading, drawing, watching television, talking, singing, physical games, and others). These categorical variables provide information about the time mothers spent on particular activities.[12] We constructed a variable counting the percentage of answers in which the mother performs the activity frequently, and use it as another dependent variable in the estimation. In this way, we could examine the different components that defined the effect of health on child development presented in the theoretical model (see Eq. 4). We could confirm that parental investment was input to child development in the theoretical model. Nevertheless, it was also an endogenous variable and, more precisely, an output of the parents' optimisation program. Hence, considering parental choices, we obtained an equilibrium value for the parental investment that depended on several variables and, in particular on children's' health at birth. For this reason, parental investment was considered as a dependent variable of interest.

We used several control variables recognised as determinants of health and cognitive development in the literature [37]. For the family environment, we used the age of the mother, average monthly income per household member in Euro, French as the home language for the mother and the father, type of housing;[13] its location in the geographic area namely rural or urban; if the mother has moved during pregnancy and if the child is looked after by someone else than the mother. We also controlled for mother's education, as it is identified as an important determinant of the health of children [12].[14] Considering the result of Panico et al. [39] which indicated that family status correlates to children's early physical health, we also controlled for this dimension by distinguishing between being married, cohabitation, civil union, and single parenting. We also included behavioural variables to capture the behaviour of the mother during pregnancy: time spent in cleaning, to do prenatal exercise, or to work at home.[15] We considered the mother's perception of a child's health when the child was 2 months and 1 year old.[16] We also controlled if children had a recognised health issue.[17] We controlled for the number of siblings when the child was 1 year, for twin birth and the sex of the child. We add a bio-demographic control variable, namely the child's ranking in the ELFE cohort.[18] Cohort ranking gives the birth order among siblings (1 indicates that the child is the firstborn). Then, we consider a technical control variables specific to the ELFE cohort. The ELFE survey was conducted on a random sample of maternity hospitals in France and comprised 349 of the 544 facilities surveyed. This choice was due to the

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[11] Note that these questions are included in the ELFE survey; we were not in a position to design them. They correspond to the methodology used by Ireton [33] and their validity is well established.

[12] It would be interesting to examine differences between maternal and paternal involvement. Nonetheless, this question cannot be addressed in our study as data for father are not well documented. We thus considered only maternal investment to construct our variable.

[13] Mothers could choose between three items to define housing type: 1—an individual house; 2—an apartment; and 3— other types.

[14] For mother education, we have: 1 "below high school" 2 "high school" 3 "bachelor" 4 "master." They represent 8%;33%; 22% and 36% of the sample, respectively.

[15] For time spent in cleaning and to do prenatal exercise, mothers were asked to indicate on a six-point scale how frequently they performed the activity per week, ranging from 1 "never" to 6 "more than 3 h per week."

[16] Respondent indicates whether the health of his child is: 1 "good," 2 "somewhat good," 3 "somewhat bad, and " 4 "'bad".

[17] 1 "yes" 0 "no".

[18] 1 means that the child is the firstborn.

distribution of maternity hospitals in terms of their size, level of medicalization, geographical location, and legal status. The fact that maternity hospitals have an unequal probability of being selected according to their size will lead to a different weight being assigned to them, to adjust the sample for statistical analysis. This weight is used in the analysis. Most of the data collection was based on regular surveys of parents. Data were collected at birth through interviews with the mothers in the maternity wards. At the ages of 2 months and 1 year, phone surveys were done with the children's parents.[19]

Empirical strategy

We analysed the impact of health at birth on child development. As a baseline, we first estimated the following empirical model

$$Y_{ir} = \alpha_0 + \beta_1 H_{ir} + \mu X_{ir} + \alpha_r + \xi_{ir}, \tag{6}$$

where Y_{ir} represents CD or parental time investment for child i living in a region r.[20] Coefficient β_1 measures the direct marginal effect of a child health status on Y_{ir}. H_{ir} is a health at birth variable that includes birth weight and gestational age. X_{ir} is a vector of child controls as described in the previous section and in Panel C of Table 1. We also added regional fixed effects. More particularly, α_r controls for time-invariant specific regional characteristics. ξ_{ir} represents the error term.

When estimating Eq. 6 using the longitudinal dataset at the child level, we controlled for several family characteristics that can affect health at birth and child development. Despite this effort, our results could still be affected by endogeneity issues. While reverse causality is excluded in our analysis (the birth outcome is measured before child's development), it may exist in several unobserved factors that could influence both health and child development. We needed to construct a measure of health endowment to overcome these common endogeneity issues. Our identification strategy used an instrumental variable approach (IV). Hence, the primary estimation relies on an IV specification to obtain an exact identification of the effect of health on child development.

To instrument child health endowment at birth, we used the ELFE interview wave corresponding to the season of advent. More precisely, the ELFE cohort represents babies born during four specific periods representing each of the four seasons in 2011: 1–4 April, 27 June–4 July, 27 September–4 October, and 28 November–5 December. As with any IV design, the critical underlying assumption for identification is that the instrument is valid. A helpful device satisfies two conditions. In our context, (i) it has to be a good predictor of birth outcomes, and (ii) birth outcomes should be the only factor explaining the impact of seasonality of birth on child development. The first condition seems to be met. A large body of literature confirms the impact of seasonality on foetal health. Strand et al. [42] provided a review of the evidence on seasonality of birth outcomes, paying particular attention to seasonal environmental and meteorological factors. They identified 20 studies that reported statistically significant seasonal patterns in birth outcomes. In addition to environmental and meteorological factors, many other mechanisms have been explored to understand seasonality in birth outcomes. They include seasonal variation in viral infections, allergies, eating patterns, or physical activities. Recently, Currie and Schwandt [20] identified higher influenza prevalence in months of birth as a factor of prematurity with winter being preponderant for viral infections. Our dataset supported this evidence as winter corresponded to wave 4. The first stage estimation in Table 3 showed that our instrumental variable had a significant and negative effect on birth outcomes ($-0.0326{**}$). The first condition was therefore satisfied.

For the exclusion restriction assumption (ii) to be valid, the birth season had to be uncorrelated with early child development and other relevant explanatory variables. There have been extensive discussions in the literature to determine if the associations between birth outcome and season of birth are driven by socioeconomic conditions around the period of conception. As emphasised by the study of Buckles and Hungerman [7], no clear consensus emerged. While these authors provided evidence relating to season of birth and maternal characteristics in the US, the study by Currie and Schwandt [20] concluded that, even if selection exists, the bias it entails is relatively small. The authors find seasonal patterns in birth weight and gestation that were not driven by the fact that heterogeneous women tended to give birth in different seasons. There is no evidence of such a relationship between family background characteristics and seasonality in France. Exploring the correlation between the four cohort waves—a proxy for season of birth—and household income, mothers' education, or marital status showed no seasonal pattern in our data. The associated box plot in Fig. 3 showed very few differences between the four birth waves for household income, mother's education, or marital status. The finding suggested that the season of birth influenced early child development mainly through the birth outcomes channel and hence satisfied relevant exclusion restrictions.[21]

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[19] Time investment, CD, and Health perception were determined at 1 year of age. Other information was gathered at the maternity hospital. HEALTH PERCEPTION was also determined at 2 months.

[20] The unit of observation is the child.

[21] Several studies have highlighted the fact that season of birth affects long-term child development because of its effect on the age of pre-school entry. As we focussed on early child development at 1 year, this channel is not relevant for our study.

Table 1 Summary statistics

Variables	Description	Mean	Sd.
	A. Dependent variables		
CD	Child development inventory index (%)	85.32	9.85
Time investment	Time spent with child (%)	57.52	18.40
	B. Independent variables		
Gest. age	Gestational age (weeks)	39.16	1.50
Birth weight	Birth weight (grams)	3309.47	499.38
	C. Control variables		
Revenue	Average monthly income per household member (Eur)	1631.33	1008.69
Meduc	Level of mother's education	2.87	1.00
1	Below high school	0.07	0.27
2	High school	0.33	.47
3	Bachelor	0.21	0.41
4	Master	0.36	0.48
Mage	Mother's age	30.80	5.06
Family status	Family status	2.39	1.22
1	Married with the father of the child	0.37	0.48
2	Civil union with the father of the child	0.11	0.32
3	Cohabiting in couple with the father of the child	0.25	0.43
4	Other	0.25	0.43
Childcare	The child is look after by someone else than the mother (=1 if yes)	0.13	0.33
Relocation	Move during pregnancy (=1 if yes)	0.13	0.33
House type	Type of housing	1.62	0.69
1	House	0.5	0.5
2	Flat	0.38	0.48
3	Others	0.11	0.32
Urban	Urban area of living (=1 if yes)	0.56	0.50
Exercise	Prenatal exercise	0.27	0.77
Clean time	Time spent to clean up	2.56	1.48
Home working	Work at home during pregnancy (=1 if yes)	0.04	0.19
Mlenghome	Mother speaks french at home (=1 if yes)	0.94	0.23
Flenghome	Father speaks french at home (=1 if yes)	0.97	0.18
Health percept. 2M	Mother's perception of child health at two months	1.14	.39
Health percept. 1Y	Mother's perception of child health at 1 year	1.20	0.44
Health issue	Recognised health issues (=1 if yes)	0.01	0.12
Siblings	Number of siblings	0.83	0.93
Sex	Gender (=2 if male)	1.49	0.50
Twins	Twins (=1 if yes)	0.03	0.17
Cohort ranking	Child births' order in the ELFE cohort	1.83	1.01
Cohort weight	Cohort ELFE weight (%)	67.98	60.50
	D. Instrumental variable		
Season Of Birth	ELFE Waves	2.75	1.05

Time period covered in the analysis is 2011 and 2012, and the unit of analysis is the child-wave region. There are 13,235 observations in the studied sample. A detailed description of child development can be found in the Appendix Tables

We then estimate the following IV model:

$$H_{ir} = \alpha_1 + \beta_2 \text{Season\_of\_Birth}_{ir} + \delta X_{ir} + \omega_r + \epsilon_{ir} \tag{7}$$

$$Y_{ir} = \alpha_2 + \beta_3 \hat{H}_{ir} + \mu X_{ir} + \alpha_r + \xi_{ir}, \tag{8}$$

where health of child i, living in region r (H_{ir}) in Eq. 8, has been instrumented by the season of birth from Eq. 7. Coefficient β_3 in Eq. 8 represents our coefficient of interest and

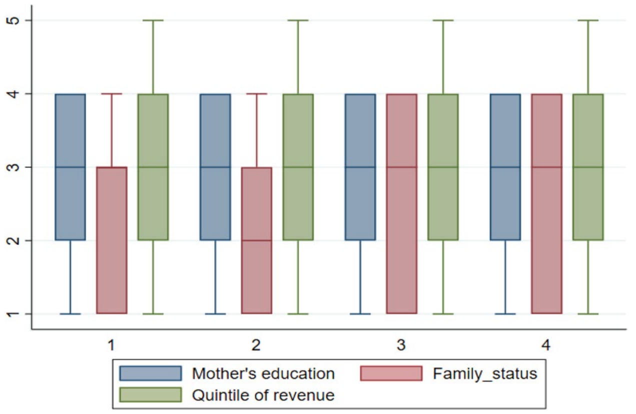

Fig. 3 Season of birth and socioeconomic characteristics. This figure represents box plots of mother's education, household's revenue, and family status over season of birth. The *X* axis represents the 4 cohort waves

measures the causal effect of a child's health status on CD. Both equations again rely on regional fixed effects as well as a vector of controls for child characteristics. Nevertheless, we should note that the IV estimator only captures the effects among the compliers, whose health at birth is impacted by the variation of season of birth. We also underline some empirical limitations in the empirical section.

Results

The impact of health on early child development

We start by examining the effect of health at birth on child development ($\frac{d\mathrm{CD}_i}{dH_i}$ in the theoretical model). Figure 4 provides a scatter plot of the relationship between birth weight and child development as well as the relationship between gestational age and child development.

There is a direct relationship between gestational age and our index of child development; child development has a strong positive relationship with gestational age: the higher the gestational age, the higher the index of child development. By contrast, this measure of human capital exhibits no clear association with birth weight.

OLS analysis

Table 2 provides regression estimates of Eq. 6 (OLS) which are largely analogous to this figure. In Table 2, we present the results on the full sample using gestational age (Columns 1–2) or birth weight (Columns 3–4) as health indicators.

Consistent with Fig. 4, Column 1 shows a positive relationship between the gestational age and child development, not controlling for child characteristics. In Column 2, we controlled for additional child characteristics. The gestational age leads to an increase in child development of 0.6 % on the total sample. Table 2 repeats the exercise in Columns 3 and 4 using birth weight. Column 4 reveals a positive effect of birth weight on child development which is very small. It was in line with the analysis of Conti et al. [14], underlining that birth weight is not necessarily a relevant proxy of health at birth.

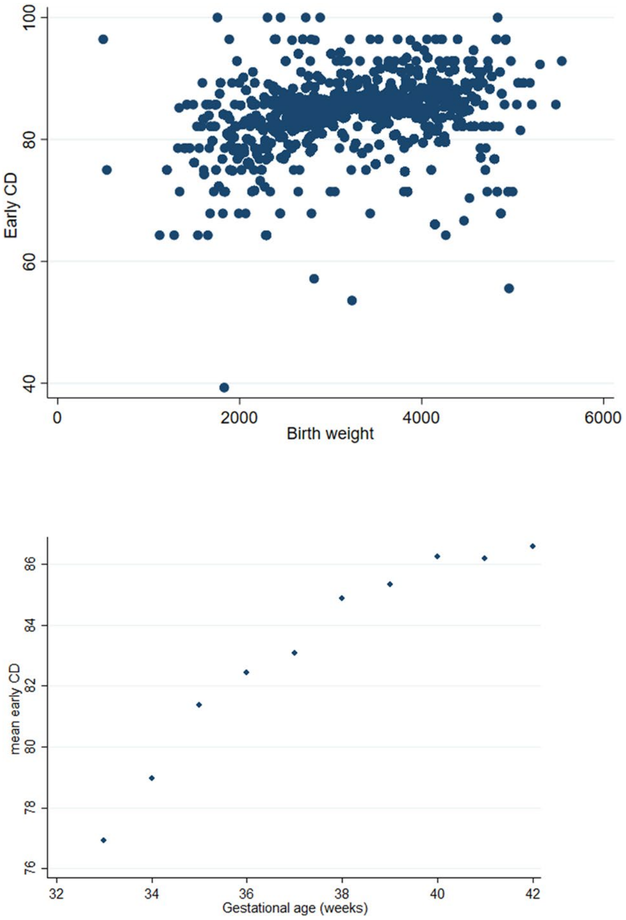

Fig. 4 The relationship between early child development and birth weight or gestational age. These figures plot the descriptive relationship between child development and birth weight or gestational age. The horizontal axis measures birth weight or gestational age. The vertical axis measures child development. Note that the cohort only interviewed mothers with babies from minimum 32 weeks of gestational age

Turning to control variables, our study shows that being a girl has a positive correlation with child development, in line with the literature that revealed the gender gap in educational attainment in favour of women (see [28], forarecentcontribution). Our results suggest that the gender gap is observed very early. Mothers' age is negatively related to child development. This is in line with the evidence which showed that risk aversion increases with age [32], while

Table 2 The impact of health on child development—OLS estimation

	Dependent variable: early child development			
	(1)	(2)	(3)	(4)
Gest. age	0.812***	0.597***		
	(0.0572)	(0.0787)		
Birth weight			0.00190***	0.00163***
			(0.000174)	(0.000238)
Revenue	−0.000299***	−0.0000658	−0.000302***	−0.0000713
	(0.0000934)	(0.000142)	(0.0000940)	(0.000143)
Meduc	−0.0914	0.233*	−0.0647	0.252*
	(0.0949)	(0.140)	(0.0956)	(0.141)
Mage		−0.175***		−0.167***
		(0.0290)		(0.0293)
Childcare		0.620**		0.683**
		(0.315)		(0.318)
Relocation		0.643*		0.606*
		(0.329)		(0.332)
Siblings		0.590*		0.478
		(0.309)		(0.312)
Family_status				
2		-0.638**		−0.564*
		(0.300)		(0.301)
3		0.277		0.353
		(0.263)		(0.265)
4		1.065		1.109*
		(0.657)		(0.662)
Twins		-2.269***		−2.500***
		(0.710)		(0.708)
Sex		1.602***		1.873***
		(0.215)		(0.218)
House type				
2		0.582**		0.640**
		(0.261)		(0.262)
3		0.335		0.230
		(1.849)		(1.852)
Health perception 1 year		−0.987***		−0.983***
		(0.248)		(0.249)
Health perception 2 month		−0.387		−0.405
		(0.288)		(0.290)
Health issue		−1.491**		−1.607**
		(0.724)		(0.728)
Exercice		0.482***		0.491***
		(0.129)		(0.130)
Clean time		0.209***		0.240***
		(0.0768)		(0.0772)
Home working		0.706		0.770
		(0.571)		(0.580)
Mlenghome		−0.102		0.0367
		(0.763)		(0.771)
Flenghome		−0.476		−0.334
		(0.811)		(0.816)
Urban		0.643**		0.685**

Table 2 (continued)

	Dependent variable: early child development			
	(1)	(2)	(3)	(4)
		(0.271)		(0.272)
Cohort ranking		−0.502		−0.532*
		(0.308)		(0.311)
Cohort weight		0.0103***		0.0106***
		(0.00267)		(0.00269)
Regional FE	Yes	Yes	Yes	Yes
Observations	13235	7711	13080	7631
R2 adjusted	0.0217	0.0445	0.0159	0.0431
F test	13.25	8.985	9.796	8.629

This table estimates the impact of gestational age and birth weight on cognitive development.

The dependent variable is the Early child development. All estimations contain regional fixed effect.

Standard errors (in parenthesis)

Statistical significance is denoted by: $*p < 0.10$, $**p < 0.05$, $***p < 0.01$

parental risk aversion has a significant negative effect on children's educational attainment [11]. Being look after by someone else than the mother is positively related with child development, suggesting childcare is of good quality. In fact, this positive effect on early development depends on the quality of childcare and socioeconomic background [8]. The coefficient of relocation is significant and positive, which seems to suggest that relocation offers a more stimulating learning environment, which would have positive repercussions on children's health at birth [43]. Living in an urban area is positively related to child's health. Douthit et al. [25] highlighted the existence of essential barriers to health care access in rural areas. There is also a positive correlation between engaging in prenatal exercises or spending time in cleaning during pregnancy and child development. In contrast, twins' birth as specific child health disabilities at 1 year is negatively related to child development. Mother's education was positively related to child development in the simple OLS, while the coefficient for household income was not significant in the model with control variables (Columns 2 and 4). A possible explanation is that a household's income can affect child development through several channels (as described in the theoretical model) that can play in opposite direction. For example, the opportunity cost to invest in children differs among heterogeneous households, which can mitigate the assumed positive effect of income/education on child development.[22] The coefficients related to the number of siblings, house type, family status, and birth order are significant and going in the right direction.

Columns 1, 2, 4, and 5 of Table 7 in the Appendix repeat the previous exercise done in Table 2 with different specifications as robustness checks. In the first panel, we remove one twin from the sample over the 268 pairs of the dataset's twins. Twins share the same socioeconomic characteristics which could bias the estimation results. The second panel adds the time parents spend with their child as new control variables. This is in line with the definition of the child development function presented in the theoretical part, which defined time investment as an input to form child development. In the third panel, we follow Conti et al. [14]'s methodology, controlling for gestational age. Indeed, to identify the effect of health variables at birth (notably foetal growth indices) on children's cognitive development and health capital at different ages, Conti et al. [14] controlled for gestational age at birth. We finally added wave fixed effect to consider specific impacts due to temporal variation. The four panels support our previous results. Gestational age has a positive effect on child development, while birth-weight impact stays very low. The size of coefficients is nearly similar to those in Table 2.

Using the same exercises as those shown in Table 2, we present in Table 8 of the Appendix the results for the different subcategories of the child development inventory. Gestational age has a positive and highly significant effect on expressive language, comprehensive language, self-help scales, and fine and gross motor scales. The gross motor's coefficient is exceptionally high, in line with the literature [24]. The effect on a social scale is not significant. This can be explained by the fact that it is difficult to capture heterogeneity in human capital at 1 year examining social activities.

Instrumental analysis

To examine if the significant effect of gestational age is robust, Table 3 presents the results with the instrumental variable.

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[22] The study of Del Boca et al. [22] provides some arguments in this sense.

Table 3 The impact of health on early child development: 2SLS estimation

2nd stage		
Dependent variable	Early child development	Early child development
	(1)	(2)
Gest. age	11.62*	
	(6.435)	
Birth weight		– 0.0923
1st stage		
Dependent variable	Gest. age	Birth weight
	(1)	(2)
Season of birth	-0.0311**	3.999
	(0.0154)	(5.162)
Control variables	Yes	Yes
Regional FE	Yes	Yes
Observations	7711	7631
R2 Adjusted	0.0929	0.108
F test	18.54	21.62
F test of excluded instrument	4.20**	1.14

This table displays both the first stage and second stage of the 2SLS estimation using season of birth as an instrument

All estimations contain regional fixed effect

Standard errors (in parenthesis)

Statistical significance is denoted by: $*p < 0.10$, $**p < 0.05$, $***p < 0.01$

Results of the IV analysis (Eq. 7) are split into two panels. The first one corresponds to the 2SLS estimation, while the second one highlights the first stage. More precisely, the first stage of the estimation of the IV analysis emphasises that our instrumental variable has a highly significant effect on gestational age (Column 1). As expected, the result is negative. In line with Currie and Schwandt [20] that underline that higher influenza prevalence in winter explains an increase in prematurity, our results show a decrease in gestational age going closer to winter. Similar to Currie and Schwandt [20], the season of birth does not significantly affect birth weight. We also conducted an F test to ensure that our instrument is relevant. While small, the F-statistic of a joint test whether all excluded instruments are significantly different from zero is positive and significant (Table 3).

Columns 3 and 6 of Table 7 in the Appendix repeat the exercise done in the second stage of Table 3 with different specifications as robustness checks. The fourth panel does not show coefficients for IV as season of birth cannot be used as an instrument as well as fixed effects. The birth weight is not significant in the IV estimation, in line with the argument previously presented. As for OLS, the IV analysis emphasises that a 1-week increase in gestational age increases child development. Note that IV estimates are larger than OLS estimates (in line with Broner et al. [6]). We are cautious with this increase of the coefficient's size, which may be due to measurement error specific to our instrument. We thus prefer to refer to OLS for coefficient interpretation. More precisely, from OLS, a 1-week increase in gestational age increases child development by roughly 0.6% from the baseline mean.

Parental investment and health at birth

Then, we examined whether and how parental investment depends on health at birth. No clear evidence exists on this point, and the theory tells that it is important to examine it to understand the relationship between health at birth and a child's development. As shown previously, the theoretical model predicts that health at birth affects the child's development through direct biological effects and through behavioural responses (time investment). Table 2 highlights that the global effect is positive. To disentangle both effects, we treated time investment as an output variable and estimated the impact of health on it in Table 4. Therefore, we repeated the exercise done in Table 2 replacing child development by time investment as a dependent variable.[23] We found no significant effect of gestational age nor birth weight on time investment in each of our specifications.[24] This latter result suggests that time investment and health at birth are not complement nor substitute as discussed in the previous theoretical section. Concerning Proposition 1 from the theoretical section, our empirical results show that the sensitivity of early child development to health in France does not depend on parental time investment $\left(\frac{\partial e_i}{\partial H_i} \text{ is not significantly different from } 0\right)$. Thus, we can assess that the significant effect of health at birth on early child development, $\frac{d\mathrm{CD}_i}{dH_i}$, observed in Table 2, is only related to a purely biological effect, $\frac{\partial \mathrm{CD}_i}{\partial H_i}$.

The next section estimates the effect of gestational age and birth weight on child development with respect to socioeconomic characteristics.

The impact of health on early child development with respect to socioeconomic characteristics

Given that we have found an effect of health at birth on child development, we now turn our attention to the impact of

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[23] By definition, in the theoretical model, there is a positive relationship between parental time investment and a child's development. This property is widely admitted and formalised in the literature. Our study did not examine this relationship, even if Table 7 in the Appendix provides some intuition about it.

[24] The impact of birth weight is significant in Column 3, but this result does not hold when adding relevant control variables.

Table 4 The impact of health on time investment

	Dependent variable: parental time investment			
	OLS estimation			
	(1)	(2)	(3)	(4)
Gest. age	−0.125	−0.121		
	(0.109)	(0.149)		
Birth weight			−0.00113***	−0.0000458
			(0.000329)	(0.000450)
Revenue	−0.000236	−0.000338	−0.000249	−0.000348
	(0.000177)	(0.000269)	(0.000178)	(0.000270)
Meduc	−0.421**	0.0616	−0.396**	0.0779
	(0.181)	(0.264)	(0.181)	(0.266)
Mage		−0.0570		−0.0719
		(0.0548)		(0.0553)
Childcare		−0.437		−0.529
		(0.596)		(0.601)
Relocation		−0.308		−0.363
		(0.621)		(0.626)
Siblings		−1.471**		−1.394**
		(0.584)		(0.589)
Family status				
2		−0.139		−0.0999
		(0.567)		(0.569)
3		1.406***		1.436***
		(0.498)		(0.501)
4		0.0157		−0.0599
		(1.243)		(1.250)
Twins		−3.355**		−3.029**
		(1.343)		(1.338)
Sex		1.129***		1.082***
		(0.405)		(0.412)
House type				
2		1.424***		1.398***
		(0.493)		(0.496)
3		−0.635		−0.650
		(3.494)		(3.498)
Health perception 1 year		−0.667		−0.635
		(0.468)		(0.471)
Health perception 2 month		0.0383		0.0468
		(0.545)		(0.547)
Health issue		1.581		1.710
		(1.369)		(1.375)
Exercice		0.530**		0.546**
		(0.244)		(0.245)
Clean time		0.449***		0.469***
		(0.145)		(0.146)
Home working		1.111		1.292
		(1.080)		(1.096)
Mlenghome		−2.436*		−2.450*
		(1.443)		(1.457)
Flenghome		3.282**		3.398**
		(1.532)		(1.541)

Table 4 (continued)

	Dependent variable: parental time investment			
	OLS estimation			
	(1)	(2)	(3)	(4)
Urban		1.198**		1.141**
		(0.512)		(0.515)
Cohort ranking		−1.129*		−1.184**
		(0.583)		(0.588)
Cohort weight		−0.00201		−0.00126
		(0.00506)		(0.00508)
Regional FE	Yes	Yes	Yes	Yes
Observations	13024	7711	12874	7631
R^2 adjusted	0.00584	0.0294	0.00662	0.0295
F test	0.00584	0.0294	0.00662	0.0295

This table estimates the impact of gestational age and birth weight on time investment

The dependent variable is the parental time investment variable

All estimations contain wave and regional fixed effect

Standard errors (in parenthesis)

Statistical significance is denoted by: $*p < 0.10$, $**p < 0.05$, $***p < 0.01$

health on child development concerning the family's socioeconomic status. We explore whether there is evidence that the impact of health at birth on child development differs based on parental income or education when used as proxy for socioeconomic status. Shiko and Eskil [41] highlighted the importance of exploring the potential differential consequences of health at birth on child development. This offers insight into the mechanism behind the estimated effects of birth health status.

Figures 5 and 6 show the estimated coefficient of the impact of gestational age or birth weight on early child development by decile of revenue and level of education. They are estimates drawn from models applied separately without control variables for each decile of income or educational level. The objective was to determine some correlational statistics before using the interaction models. Figure 5 shows that coefficients are slightly different regarding decile of revenue although not significant. As shown in Fig. 6, the impact of health at birth on child development is also nearly similar to education's.

The figures show that poor neonatal health may not disproportionately affect children growing up in high socioeconomic status families compared to children in lower socioeconomic classes.

To explore these potential sources of heterogeneity in the effect of birth health status on early development, we analysed in line with Currie and Stabile [21] and Wei and Feeny [45] by adding an interaction term in the regression. We included the interaction of birth health and parental income and birth health and mothers' education.

Following theoretical predictions, all else being equal, the effect of health at birth on child development for high-income/educated households may be lower, more significant, or identical to that of low-income/educated households. All configurations are possible depending on the complementarity of inputs. Table 5 shows the estimated coefficient of the impact of gestational age or birth weight on early child development with interaction terms.

Columns 1 and 2 of Table 5 show the estimates of the impact of gestational age interacting with revenue using OLS and IV estimation, respectively. Columns 3 and 4 show the estimates of gestational age's impact interacting with education. In Columns 5–8, the same exercise was repeated for birth weight. Analogous to Figs. 5 and 6, we once again found no significantly different effects of health at birth on child development with respect to the level of parental revenue or the level of mother's education. Again, we found a positive coefficient for gestational age in the OLS estimation and a lack of significance for birth weight.

The results indicate that the effects of health at birth are roughly the same for children from different socioeconomic classes. Our findings suggest that, in France, there are no disparities among very young children concerning the consequences of poor health status at birth. They also indicate that, despite potentially different family environments, treating health issues at birth prevents an increase in socioeconomic inequality. Access to health care and medical practices in France for young children appears equal.

It is widely accepted that child development is not an exclusively familial matter. There is space for policy

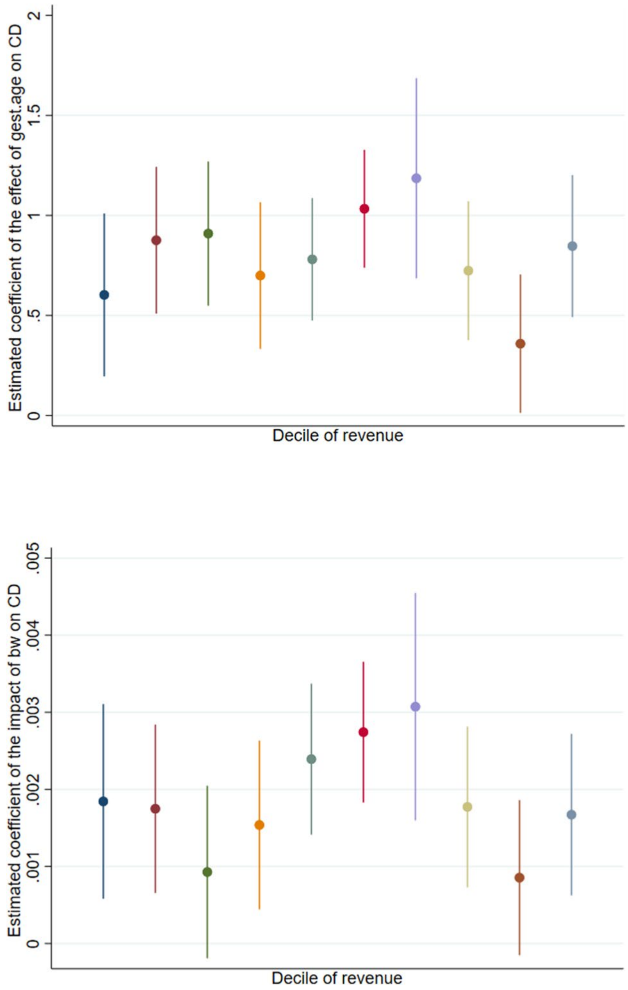

Fig. 5 Estimated coefficient of the impact of gestational age and birth weight on early child development by decile of revenue. The horizontal axis shows deciles of revenue (Revenue). The vertical axis shows the estimated coefficient of the impact of gestational age or birth weight on early child development for each decile

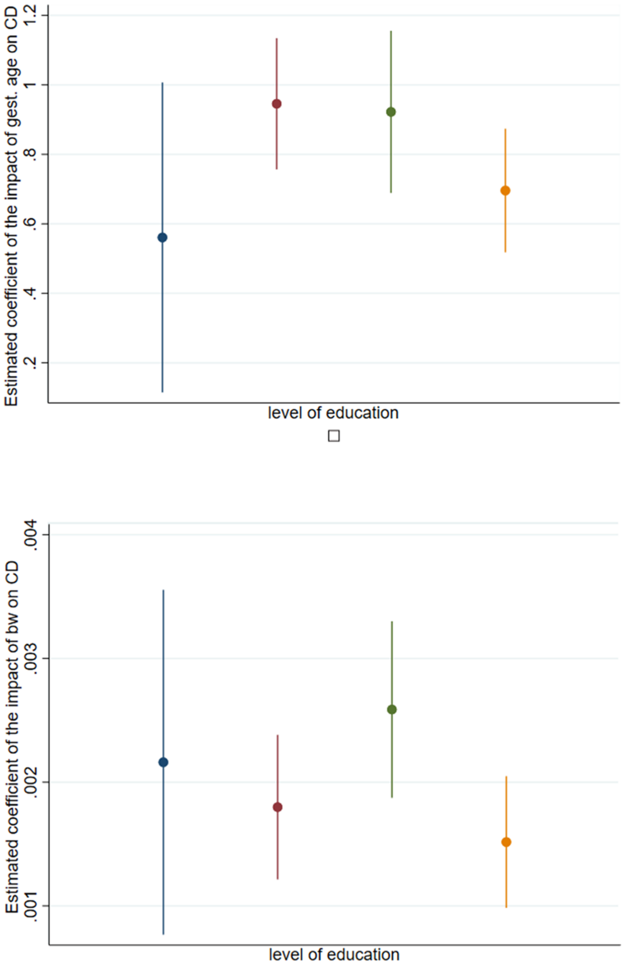

Fig. 6 Estimated coefficient of the impact of gestational age and birth weight on early child development by level of education. The horizontal axis shows four level of education with respect to the Meduc variable. The vertical axis shows the estimated coefficient of the impact of gestational age or birth weight on early child development for each subsample of education

intervention to improve it and address the unequal distribution of initial endowment across the population. Our analysis supports this statement given the positive effect of health at birth on future child development. In this sense, our results support the “1000 first days” strategy of the French Government, which included public action during the prenatal period to improve health outcomes at birth.

Conclusion

We used an OLS and an IV estimation approach, based on the season of birth, to identify the impact of health at birth on France’s human capital. The analysis was conducted on the child level controlling for a wide set of child characteristics and regional fixed effects. The results provide the first estimation of health’s impact at birth on early child development at the national level in France. Estimation results indicate an increase in 1 week of gestational age between week 32 and week 42 at birth increases the average early child development at 1 year of age by 0.6%. Combining empirical and theoretical approaches allowed us to underline that this positive and statistically significant effect is mainly biological. Poor health status does not modify significantly parental investment in children, such that the way health at birth affects child development is not dependent of parental behaviour. This paper’s additional contribution consists of distinguishing the effect of health at birth on human capital concerning parents’ level of income and education. Our results showed no differential effect among socioeconomic factors suggesting an efficient treatment of health issues at a very early age in France. Redistributive

Table 5 The impact of health on child development interacted with revenue or education

	Dependent variable: early child development							
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Gest. age*Revenue	0.0000814	− 0.0473						
	(0.0000961)	(0.0920)						
Gest. age*Meduc			− 0.0127	10.19				
			(0.0162)	(35.00)				
Birth weight*Revenue					0.000000140	0.0000819		
					(0.000000257)	(0.0000980)		
Birth weight*Meduc			–				− 0.0000523	0.0179**
							(0.000153)	(0.00894)
Gest. age	0.452**	102.8	0.650***	− 99.90				
	(0.189)	(198.8)	(0.103)	(344.9)				
Birth weight					0.00138***	− 0.186	0.00185***	− 0.0826**
					(0.000525)	(0.225)	(0.000671)	(0.0420)
Revenue	−0.00326	1.857	−0.0000677	0.000672	− 0.000546	− 0.277	− 0.0000720	0.000173
	(0.00378)	(3.613)	(0.000142)	(0.00299)	(0.000882)	(0.332)	(0.000143)	(0.000278)
Meduc	0.236*	−2.889	0.751	-410.8	0.254*	1.988	0.433	-61.56**
	(0.140)	(6.130)	(0.676)	(1411.7)	(0.141)	(2.161)	(0.547)	(30.84)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7711	7711	7711	7711	7631	7631	7631	7631
R2 Adjusted	0.0445	−36.57	0.0445	−118.4	0.0430	− 16.02	0.0429	− 1.954
F test	8.805	0.227	8.802	0.0653	8.447	0.482	8.443	2.766

This table reports estimates of the impact of gestational age and birth weight when interacting with revenue and education on child cognitive development.

The dependent variable is early child development. All estimations contain wave and regional fixed effect.

Standard errors (in parenthesis)

Statistical significance is denoted by: $*p < 0.10$, $**p < 0.05$, $***p < 0.01$

health care systems in France, ensuring equal access to care, may explain this result.

As health at birth was identified as a determinant of child development, our study emphasises the need to identify the determinants of potential factors that cause unequal health at birth and design policies to address these inequalities. Air pollutant exposure could be one such factor.[25] Public policies aimed at addressing air pollution issues would thus have beneficial effects on human capital at later ages and its distribution across society. Public investment to reduce perinatal health inequalities and reinforce accessibility of maternity services, particularly in rural areas, is also an important lever.[26] A logical direction for further research would be to further explore such policy implications in more depth. Future research should also aim to understand the role of parental time investment in the effect of health at birth on human capital development during childhood, particularly through studying child development after 1 year of age. Finally, examining whether the positive association of gestational age and child development is still observed when children are older is an avenue that should be explored.

The findings of this study must be seen in the light of some limitations. Possible measurement errors on key CD or health variables may exist. Missing data may point towards selection bias, but we can state that we observed a very low correlation between income and non-responses to the questions used to build the child development index. Our data on the family's characteristics may also have excluded unobservable behavioural variables, which prevents us from examining our instrument's exogeneity condition. Finally, it is essential

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[25] According to [17] or [31], children from lower socioeconomic households were found to be more vulnerable to pollution.

[26] [13] showed that long travel times, due to the closest maternity units in rural France being far, were associated with an increase in the risk of poor perinatal outcomes.

Table 6 Child development inventory based on the methodology of Ireton [33]

Questions	Scale
Interested in his(her) image in a mirror	Social scale
Greets people with "Hi" or similar expression	Social scale
Feeds self a cookie	Self help scale
Picks up a spoon by the handle	Self help scale
Removes socks	Self help scale
Chews food	Self help scale
Drinks in a glass/cup	Self help scale
Sits without help	Gross motor scale
Stands steady without support	Gross motor scale
Stands up without help	Gross motor scale
Sidesteps around furniture or crib while holding on. or walks	Gross motor scale
Walks without help	Gross motor scale
Picks up objects with one hand	Fine motor scale
Holds two objects at the same time, one in each hand	Fine motor scale
Uses two hands to pick up large objects	Fine motor scale
Picks up small objects, using thumb and one finger	Fine motor scale
Transfers objects from one hand to the other	Fine motor scale
Builds a tower of two or more blocks	Fine motor scale
Makes sounds like he(she) is talking in sentences. Or used to	Expressive language scale
Jabbers	Expressive language scale
Points to things	Expressive language scale
Calls his(her) parents "Mama" or "Dada" or similar name	Expressive language scale
Understands "No"; stops	Language comprehension scale
Responds to his(her) name.	Language comprehension scale
Imitates some sounds that parents make. Or used to	Language comprehension scale
Comes when called	Language comprehension scale
Waves "bye-bye" or good-by	Language comprehension scale
Hands a toy to parents when asked	Language comprehension scale

to underline that the ELFE cohort study has only been conducted once. The data do not allow us to perform a relevant dynamic analysis to examine the relationship between unfavourable health at birth and early child development across time.

Appendix

Child development

To select questions of the ELFE cohort relevant to build the child development index, we use the methodology of Ireton [33]. Ireton [33] provides a list of questions to appreciate the child development during the first year of life (Appendix Tables 6):

Table 7 Robustness checks

	Dependent variable: early child development					
	OLS	OLS	IV	OLS	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	Without the second twin					
Gest. age	0.781***	0.595***	10.76**			
	(0.0587)	(0.0790)	(5.446)			
Birth weight				0.00179***	0.00162***	-0.117
				(0.000178)	(0.000239)	(0.190)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	No	Yes	Yes	No	Yes	Yes
Observations	13035	7615	7615	12881	7535	7535
R^2 adjusted	0.0201	0.0438	− 2.046	0.0146	0.0424	−31.31
F test	12.17	8.758	2.441	8.940	8.407	0.227
	With time investment					
Gest. age	0.829***	0.600***	13.86*			
	(0.0565)	(0.0784)	(7.503)			
Birth weight				0.00205***	0.00160***	-0.0894
				(0.000172)	(0.000237)	(0.100)
Time investment	0.105***	0.0954***	0.105***	0.107***	0.0957***	0.0924***
	(0.00455)	(0.00594)	(0.0143)	(0.00459)	(0.00598)	(0.0330)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	No	Yes	Yes	No	Yes	Yes
Observations	13019	7541	7541	12869	7463	7463
R^2 adjusted	0.0604	0.0755	-3.455	0.0558	0.0743	-18.34
F test	34.48	13.32	2.588	31.40	12.99	0.594
	With birth weight and gestational age in the same regression					
Gest. age	0.673***	0.448***	11.00**	0.673***	0.448***	7.243*
	(0.0685)	(0.0907)	(5.208)	(0.0685)	(0.0907)	(4.092)
Birth weight	0.000805***	0.000982***	−0.0144*	0.000805***	0.000982***	−0.0410
	(0.000206)	(0.000272)	(0.00758)	(0.000206)	(0.000272)	(0.0253)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	No	Yes	Yes	No	Yes	Yes
Observations	13080	7631	7631	13080	7631	7631
R^2 adjusted	0.0230	0.0460	−1.659	0.0230	0.0460	−2.959
F test	13.34	8.998	3.134	13.34	8.998	2.157
	With wave fixed effect in the OLS estimation					
Gest. age	0.849***	0.643***	–			
	(0.0567)	(0.0777)	–			
Birth weight				0.00196***	0.00166***	–
				(0.000172)	(0.000235)	–
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
Wave FE	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	No	Yes	Yes	No	Yes	Yes
Observations	13235	7711		13080	7631	
R^2 adjusted	0.0456	0.0724		0.0390	0.0704	
F test	24.39	13.53		20.68	13.03	

This table varies the specification of the model to look at the impact of gestational age and birth weight on cognitive development

The dependent variable is the Early child development. All estimations contain regional fixed effect

Standard errors (in parenthesis)

Statistical significance is denoted by: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$

Table 8 Subcategories

	Dependent variable: early child development					
	Comp. scale	Exp. scale	Soc. scale	Self. scale	Gmotor scale	Fmotor scale
	(1)	(2)	(3)	(4)	(5)	(6)
Gest. age	0.428***	0.673***	−0.0500	0.525***	1.422***	0.434***
	(0.108)	(0.188)	(0.0940)	(0.150)	(0.215)	(0.0973)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2 adjusted	0.0234	0.0245	0.00132	0.0140	0.0333	0.0117
F test	4.897	5.086	1.215	3.311	6.616	2.923
Observations	7495	7495	7495	7495	7495	7495
Birth weight	0.00117***	0.00106*	−0.000224	0.00223***	0.00352***	0.000974***
	(0.000328)	(0.000570)	(0.000284)	(0.000452)	(0.000649)	(0.000294)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2 adjusted	0.0233	0.0232	0.00150	0.0155	0.0312	0.0106
F test	4.840	4.822	1.243	3.541	6.183	2.735
Observations	7416	7416	7416	7416	7416	7416

This table varies the specification of the model to look at the impact of gestational age and birth weight on cognitive development

The dependent variable is the Early child development. All estimations contain regional fixed effect

Standard errors (in parenthesis)

Statistical significance is denoted by$*p < 0.10$, $**p < 0.05$, $***p < 0.01$

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Pollution, children's health and the evolution of human capital inequality[☆]

Karine Constant[a,*], Marion Davin[b]

[a] Université Paris Est, Erudite, UPEC, Créteil, France
[b] CEE-M, Univ. Montpellier, CNRS, INRAE, SupAgro, Montpellier, France

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ABSTRACT

This article examines how pollution and its health effects during childhood can affect the dynamics of inequalities among households. In a model in which children's health is endogenously determined by pollution and the health investments of parents, we show that the economy may exhibit inequality in the long run and be stuck in an inequality trap with steadily increasing disparities, because of pollution. We investigate if an environmental policy, consisting in taxing the polluting production to fund pollution abatement, can address this issue. We find that it can decrease inequality in the long run and enable to escape from the trap if the emission intensity is not too high and if disparities are not too wide. Otherwise, we reveal that a policy mix with an additional subsidy to health expenditure may be a better option, at least if parental investment on children's health is sufficiently efficient.

1. Introduction

Pollution is one of the most important threat for health. According to the World Health Organization, approximately one-quarter of the global disease burden is due to modifiable environmental factors, representing 13.7 million deaths a year (WHO, 2016). There is considerable evidence that pollution, and in particular air pollution, has a positive and significant effect on morbidity - i.e. the rate of disease in the population – and mortality – i.e. the rate of death.[1] While pollution affects the entire population, children are identified as particularly vulnerable to its damaging health effects (see, e.g., Sacks et al., 2011; Beatty and Shimshack, 2014 or WHO, 2018). Empirical studies identify that these larger effects are due to both a larger vulnerability of children, mainly because their lungs, brains and immune system are not completely developed, and a larger exposure, as they spend more time engaging in physical activity outside — where air pollution levels are usually larger (see, e.g., Bateson and Schwartz, 2007).

Such detrimental effects on children's health are not only a short-term issue but persist later in life (see Currie et al., 2014 for a literature review). Childhood exposure to pollution is found to be associated with poor adult health. Moreover, by increasing school absenteeism (see, e.g., Park et al., 2002) and affecting negatively cognitive and learning abilities of children (see, e.g., Factor-Litvak et al., 2014), environmental degradation deteriorates also human capital formation. Through all these channels, the exposure of children to pollution implies long-term negative consequences on human capital and income when adult, representing a persistent threat to the well-being and abilities of individuals.

In addition, the health effects of pollution are characterized by their unequal distribution within a given generation. Children from households of lower socioeconomic status – in particular in terms of education – are found to be more vulnerable to pollution than those from more privileged households, even if they are exposed to similar levels (see, e.g., Neidell, 2004 or Currie, 2009). Those differences stem from the fact that wealthier and more educated parents are more likely to provide a cleaner environment to their children, but also to invest more in their children's health (see, e.g., Currie et al., 2014).

All these facts lead us to wonder about the potential role of childhood exposure to pollution in the intergenerational transmission of inequality among agents. In this paper, we aim at examining how this mechanism could occur, what would be

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[*] Corresponding author.
E-mail addresses: karine.constant@u-pec.fr (K. Constant), marion.davin@umontpellier.fr (M. Davin).

[1] See, e.g., Ostro (1983); Hanna and Oliva (2015); Graff Zivin and Neidell (2012) on the effect of air pollution on morbidity and Bell and Davis (2001); Pope et al. (2002) ; Bell et al. (2004); Evans and Smith (2005) or Beelen et al. (2014) on its effect on mortality.

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the consequences, and therefore, whether environmental policies could be a part of the solution to overcome the inequality issue.

We focus on the dynamics of inequality across generations because inequality represents a major challenge for our society. Since 1980, the gap between rich and poor is at its highest level in most developed countries and follows an upward trend (see, e.g., OECD, 2015 or UN, 2020). Such disparities are multidimensional and concern economic, social and health dimensions. Large health inequalities exist in the population according to the socioeconomic status of individuals. According to the OECD (2019), *"across all countries, people in the lowest education category are twice more likely to view their health as poor compared to those with tertiary education"*, and *"people without high-school diploma can expect to live about 6 years less than those with tertiary education"*. These disparities may entail huge costs for society — in terms of well-being, health and social costs, productivity loss, discouraged investments, wasted potential *etc*. Moreover, a growing number of empirical and theoretical studies emphasize the net detrimental effect of inequality on long-term economic growth through its negative effect on human capital accumulation (see, e.g., Galor, 2011; OECD, 2015 or Constant, 2019). For all these reasons, reducing these disparities has became an explicit goal for many governments and, for that, it seems crucial to explore the different channels through which they occur.

To study the potential role of the health effect of pollution during childhood in the transmission of inequality, we formalize an overlapping generations model, with children and parents, in which agents are heterogeneous in terms of human capital. In accordance with the results emphasized by the literature discussed earlier, we consider the effect of air pollution on children's health, the possibility for parents to invest in health care to lower this adverse effect, and the role of children's health in the acquisition of human capital.

Through a theoretical analysis and a numerical illustration, we find that the economy may exhibit different long-term behaviors according to the pollution intensity of production and the initial level of disparities between agents. When they are both sufficiently low, the economy converges toward a long-term state without inequality. However, if production is highly polluting, inequality will always persist across time – whatever the initial level of inequality – and the economy may even be caught in an inequality trap with steadily rising disparities. The underlying mechanism is the following. Parents choose the level of expenditure aiming at reducing the health effects of pollution. Their human capital being heterogeneous, so are their financial abilities and their investments, which entails a heterogeneous vulnerability to pollution among children. Pollution affects more children from poorer households, who will therefore be less able to accumulate human capital and have a lower return on the education investment. Thus, the gap among households increases at each generation due to pollution. Note that we obtain this result despite the fact that we consider no difference in terms of abilities and diminishing marginal returns of human capital accumulation that usually ensure the absence of inequality in the long run. Here, such equality would always be found without pollution. But in the presence of pollution, its detrimental effect on children's health may dominate and hence prevent human capital convergence in the long run. Thus, the exposure of children to pollution represents an important channel of intergenerational transmission of inequality.

We then explore if specific public interventions focusing on this mechanism are effective to tackle these human capital inequalities. First, pollution being the source of increasing divergence between agents, we examine the consequences of an environmental policy that consists in public maintenance funded by a tax on polluting production. Then, we also study the effects of a combination of an environmental and a health policy, through private health subsidy funded by a production tax. We obtain that an environmental policy is a good option to reduce the inequality issue in the economy but only when pollution intensity and the level of disparities among agents are not too high. Otherwise, it is not sufficient and may even reinforce inequality due to the negative income effect of the tax. In this case, we reveal that adding a health policy to the policy package could be an interesting solution. Typically, when health expenditure is sufficiently determining for health with respect to pollution, such a policy mix can prevent the economy to exhibit rising inequalities for a larger set of emission intensity.

The rest of the paper is organized as follows. Section 2 reviews the most relevant contributions related to our work. The model is presented in Section 3. Equilibria and dynamics of the economy are examined theoretically and illustrated numericaDDlly in Section 4. Section 5 is devoted to the policy implications and Section 6 concludes.

2. Literature review

This paper contributes to the growing theoretical literature on the macroeconomic consequences of health issues. By introducing endogenous mortality in standards overlapping generations models, Blackburn and Cipriani (2002) and Chakraborty (2004) point out the mutual interactions between health and the development process. As longevity affects the returns on investments such as savings and education, it may enable the economy to develop or, on the contrary, lead to permanent poverty, according to its initial conditions. Closer to our work, Chakraborty and Das (2005) and Castello-Climent and Domenech (2008) explain the persistence of disparities among the population by endogenous life expectancy. In Chakraborty and Das (2005), poorer agents are less able to invest in health to reduce their mortality risk and to improve their human capital. Thus, they have less to bequeath to the next generation. Whereas in Castello-Climent and Domenech (2008), agents' longevity depends on the human capital of their parents, which implies that their choices in terms of education and hence their living conditions when adult differ according to their parents' wealth. Bhattacharjee et al. (2017) consider a longevity determined by public and private health expenditure, with the latter being done by the parents for their children, and find that an increase in the share of private to public expenditures entails an increase in inequality. Although these studies emphasize the importance of considering the endogenous determination of agents' health, they abstract from the role of pollution in the deterioration of health. However, environmental degradation is found to have a critical detrimental effect on health (see references mentioned in the Introduction), while being also strongly linked to the economic activity. For these reasons, another strand of the literature focuses on the economic consequences of the health effects of pollution.

By focusing on workers' productivity as Van Ewijk and Van Wijnbergen (1995) or Aloi and Tournemaine (2011), or on life expectancy as Pautrel (2009), Mariani et al. (2010) and Raffin and Seegmuller (2014) or Palivos and Varvarigos (2017), these contributions show the short- and long-term macroeconomic consequences of pollution and its policy implications. Among the main results, they identify the risk for the economy to be stuck at a long-term equilibrium with poor health and low environmental quality and the major role that an environmental and/or a health policy may play in avoiding this risk and fostering economic development. In particular, Raffin and Seegmuller (2014) and Palivos and Varvarigos (2017) consider the role of both public health care expenditures and pollution on life expectancy. Raffin and Seegmuller (2014) emphasize that preventive (environmental) and curative (health) policies both improve longevity but have opposite long-term consequences: the former is appropriate for developed economies, while the latter is suitable for poor economies. Palivos and Varvarigos (2017) show that optimal environmental policies, in the form of pollution abatement activities, represent an engine of long-run economic growth and stabilization for the economy as it eliminates the possibility of permanent cycles.

In a similar vein, Raffin (2012) examines the interactions between the environment, health and development. However, while all the aforementioned contributions focus on adults' health (and most of the time on longevity), she considers the negative effect of pollution on children's learning abilities. She points out that a poor environmental quality may lead to low parental investments in education, low incomes and *in fine* poor living conditions in the long run.

Our study follows on from these contributions but we want to go one step further by studying the unequal distribution of the detrimental health effect of environmental degradation. Whereas inequality has received increasing public and academic attention recently and the health effects of pollution are found to be very unequally distributed in the population, only few studies have examined such an issue for now. Notable exceptions are Aloi and Tournemaine (2013) and Constant (2019). On the one hand, Aloi and Tournemaine (2013) consider the effect of pollution on human capital accumulation. Assuming that unskilled individuals have a lower ability to learn and are more exposed to pollution, they find that a tighter environmental policy always reduces income inequality. Here, we differ from this paper by assuming no difference in the innate skills of agents nor in their exposure to pollution. Rather, we consider the possibility for parental expenditure on health, capturing all costly activities enabling to reduce the vulnerability of children to pollution (i.e. health care and avoidance behaviors, including larger housing cost to live in a cleaner area for example). In this way, we represent endogenous disparities that depends on the level of pollution and on households' choices. It enables us to represent a more complete set of long-term behaviors of the economy and draw further conclusions as regards the efficiency of an environmental policy. On the other hand, Constant (2019) considers how an endogenous longevity of parents depending on human capital and pollution contributes to the transmission of human capital inequality by modifying the ability and the willingness of parents to invest in education. We differ from this work by studying another kind of health effect that is children's morbidity and by considering health expenditure and health policy. Thus, we highlight other mechanisms and provide a more complete analysis of the policies that can be implemented.[2]

3. The model

We consider an overlapping generations economy, with discrete time indexed by $t = 0, 1, 2, \ldots, +\infty$. Households live for two periods — childhood and adulthood. At each date t, a new generation of N agents is born. We assume no population growth so that the number of births (N) is normalized to unity. Individuals are indexed by $i = u, s$, corresponding to two groups: unskilled (u) and skilled (s), of size ξ and $1 - \xi$, respectively. The two groups of agents differ in terms of human capital, which is relatively low for unskilled individuals and relatively high for skilled individuals. More precisely, agents born in t differ only in the level of human capital of their parents ($h^u_{t-1} < h^s_{t-1}$).

3.1. Consumer's behavior

An individual of type i born in $t-1$ cares about her consumption levels when an adult c_t, about the future human capital of her child h_{t+1} through paternalistic altruism and about the environmental health of her child Θ_t. In this paper, we distinguish the concept of human capital and health in order to focus on the interactions between health and the accumulation of knowledge of individuals. The preferences of this representative agent are represented by the following utility function:

$$U(c^i_t, h^i_{t+1}, \Theta^i_t) = \ln c^i_t + \gamma \ln h^i_{t+1} + \lambda \ln \Theta^i_t, \tag{1}$$

with γ and $\lambda > 0$.

During childhood, agents devote all of their time to the acquisition of human capital. After reaching adulthood, they are endowed with h^i_t units of human capital, which they use for labor force participation, remunerated at wage w_t per unit of human capital, and they allocate their income between consumption c^i_t, the education of their children e^i_t and expenditure to improve their children's health s^i_t.

Consequently, the budget constraint for an adult of type i born in $t-1$ is

$$c^i_t + e^i_t + s^i_t = w_t h^i_t. \tag{2}$$

Focusing on the health effects of exposure to pollution during childhood, the index Θ^i_t represents the current health status of a child born in t of type i and depends on pollution P_t and parent's health expenditure s^i_t which allows to reduce the exposure and vulnerability of the child to pollution.[3] Thus, pollution does not act as a pure externality on human capital formation. For the sake of simplicity, we assume the following specific function for the environmental health of a child.

$$\Theta^i_t = \frac{\bar{\theta} s^i_t - \underline{\theta} P_t}{1 + P_t}, \tag{3}$$

with $\bar{\theta}$ and $\underline{\theta}$ two parameters > 0. This simple function exhibits relevant properties and allows to derive analytical results. It is decreasing and convex in pollution P_t (in line with Varvarigos (2010) or Raffin and Seegmuller (2014)) and linear and increasing in health expenditure s^i_t.[4] For a given level of health expenditure s^i_t, the environmental health achieves its maximal value $(\bar{\theta} s^i_t)$ when there is no pollution. On the opposite, an infinitely high level of pollution requires an infinite level of expenditure to keep the health index positive. Finally, the elasticity of Θ^i_t to pollution decreases with s^i_t, meaning that we can appreciate s^i_t as costly parental adaptive or avoidance behaviors allowing to reduce the negative impact of an increase in pollution on child development. It can be an investment during childhood under the form of health care expenditures, healthy consumption, or investment to live in a cleaner area (pollution-driven residential sorting).

Knowledge accumulation is determined by formal education e^i_t, by the parent's level of human capital h^i_t - representing the transmission of cognitive and social knowledge within the family -, and by the average human capital $\bar{h}_t$ - which represents the quality of the educational system. Moreover, as detailed previously, a consistent body of the empirical literature has demonstrated that health and pollution have key consequences on the abilities of children to learn. Therefore, we assume that the level of human capital of a child born in t h^i_{t+1} depends also on the environmental health of this child Θ^i_t.

$$h^i_{t+1} = \epsilon (\Theta^i_t)^{\alpha} (e^i_t)^{\beta} (h^i_t)^{\mu} (\bar{h}_t)^{\delta}, \tag{4}$$

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[2] Another exception – but farther given that it focuses on the demographic transition process – is Schaefer (2020) who considers the effect of unequal exposure to pollution on child mortality. He finds that it implies that a larger proportion of the population will favor quantity over quality in their fertility decisions, hence hampering economic development. Note that we focus on children's morbidity rather than on their mortality because we are studying developed countries and 99% of under-five deaths occurs in developing countries (UNICEF, 2015).

[3] As we focus on health concerns in early life and in order to simplify, we formalize the current health status of children rather than a lifelong health stock.

[4] Note that considering a function decreasing linear with pollution P_t leads to the same results, given our log utility function.

where $\epsilon > 0$ is the efficiency of human capital accumulation. The parameters α, β, μ and δ all > 0 capture the respective weights of health, education, intergenerational transmission of human capital within the family and transmission within the society. To focus on cases in which human capital convergence and human capital divergence are both possible, we formulate the following assumption.

Assumption 1.

$\alpha + \beta + \mu < 1.$

Note that the opposite assumption ($\alpha + \beta + \mu > 1$) would imply an increasing return of human capital on h^i_{t+1}, meaning that the return on the investment in education would always be larger for higher-skilled agents and lower-skilled agents would never be able to catch-up. In this scenario, human capital convergence between agents would never be possible. On the contrary, our hypothesis of diminishing return of human capital enables to consider a framework that makes convergence possible.

The consumer program is summarized as follows:

$$\max_{e^i_t, s^i_t} U(c^i_t, h^i_{t+1}, \Theta^i_t) = \ln c^i_t + \gamma \ln h^i_{t+1} + \lambda \ln \Theta^i_t \tag{5}$$

$$s.t \quad c^i_t + e^i_t + s^i_t = w_t h^i_t$$

$$\Theta^i_t = \frac{\bar{\theta} s^i_t - \underline{\theta} P_t}{1 + P_t}$$

$$h^i_{t+1} = \epsilon (\Theta^i_t)^{\alpha} (e^i_t)^{\beta} (h^i_t)^{\mu} (\bar{h}_t)^{\delta}.$$

An adult maximizes her utility taking into account her budget constraint (2), and her child's health (3) and human capital (4). A parent invests in her child's health because she obtains a direct benefit from having a healthy child and because of the positive effect it has on the future human capital of the child. Thus, child's health affects parent's utility through two channels: a direct one, whose importance is captured by λ and an indirect one whose importance depends on α and γ.[5]

Adult optimal microeconomic choices are

$$e^i_t = \frac{\gamma \beta}{\bar{\theta}(1 + \gamma\beta + \alpha\gamma + \lambda)} \left[\bar{\theta} h^i_t w_t - \underline{\theta} P_t \right] \tag{6}$$

$$s^i_t = \frac{(\lambda + \alpha\gamma)\bar{\theta} h^i_t w_t + \underline{\theta}(1 + \gamma\beta) P_t}{\bar{\theta}(1 + \gamma\beta + \alpha\gamma + \lambda)}. \tag{7}$$

A parent's health expenditure for her child s^i_t depends positively on the level of human capital of the parent and positively on the level of pollution. Indeed, parents' abilities to make such an expenditure are greater when their human capital and hence their wages are larger, while a larger level of pollution represents a larger threat to their children's health, which provides more incentives to protect their children from pollution. This is consistent with empirical evidence that reveals that the vulnerability of children to pollution, and hence their health, is endogenous and depends in particular on parental socioeconomic status. In this regard, Case et al. (2002) present evidence of a gradient between socioeconomic status and health in childhood for the US, according to which relatively richer households have children in better health. Arguments for children's health being positively related to household income rely on parental avoidance behaviors to limit air pollution exposure and investments in health care (see. Currie et al., 2014), both taken into account here with s^i_t representing all costly activities reducing the susceptibility of children.

In the same manner, education expenditure for children e^i_t depends positively on parent's human capital and negatively on pollution. On the one hand, parents with larger h^i have more means to finance their children education. On the other hand, when pollution is high, the opportunity cost of investing in education rather than in health becomes higher. As parents have limited financial means, they make a trade-off between spending for children's education and spending for children's health. Pollution tends to tip this balance in favor of health expenditure.

3.2. Production

The production of the composite good is performed by a single representative firm.[6] Output of this good is produced according to a constant return to scale technology:

$$Y_t = AH_t, \tag{8}$$

where H_t is the aggregate stock of the human capital of workers in period t and $A > 0$ measures a technology parameter.

As the size of each generation is normalized to unity, H_t is equal to the average human capital $\bar{h}_t$. Thus, production corresponds to

$$Y_t = A\left(\xi h^u_t + (1 - \xi) h^s_t\right). \tag{9}$$

The firm chooses inputs by maximizing its profit $Y_t - w_t \bar{h}_t$, such that

$$w_t = A. \tag{10}$$

3.3. Pollution

In this paper, we focus on the world's largest single environmental health risk, i.e. air pollution (see WHO, 2014). It is important to note that the health effect of such pollution is due to its level before absorption, deposition or dispersion in the atmosphere, and that the most significant health threats among air pollutants, that are particulate matter and ground-level ozone, remain only for short periods of time in the atmosphere. Indeed, their atmospheric lifetime is from minutes to weeks (see, e.g. IPCC, 2001 or USEPA, 2004). As a period in our model represents 25 years, we formalize pollution as the flow currently emitted in the economy. More precisely, pollution is a by-product of aggregate production such that

$$P_t = \nu Y_t = \nu A \bar{h}_t, \tag{11}$$

with $\nu > 0$ representing the emission intensity of production, i.e. the emission rate per unit of output.

4. Equilibrium and dynamics of the economy

At the equilibrium, agent's health spending depends positively on family income and on the average level of human capital in the economy (through its impact on pollution). Education choices being affected negatively by pollution, it decreases with the average human capital.

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[5] This assumption does not change our results. The three following configurations would lead to the same result: (i) a model in which parental expenditure in health is motivated by both direct and indirect motives (fully rational parents) (ii) a model in which only the direct motive plays, (iii) a model in which only the indirect one plays. Private choices would display the same properties and be only quantitatively affected. In the rest of the analysis, the constant C_1, defined after equation (13) and in Appendix A.4, would be modified, without any consequences for the dynamical analysis. The condition in the second item of Proposition 5 and the value for the steady state in Fig. 5 would be also modified, again without changing our conclusions.

[6] There is only one composite good in the economy that serves to consume c, to educate children e and to compensate for the adverse effect of pollution on children's health s. Its price is normalized to one for simplicity. We thus implicitly assume that education is provided by the family and that the adverse effect of pollution can be mitigated by private actions, that require to consume a part of the composite good.

Using the definition of $\bar{h}_t$ corresponding to $\bar{h}_t = \xi h_t^u + (1-\xi)h_t^s$, we can express the dynamics of the economy through the dynamics of both unskilled and skilled human capital (h_t^u and h_t^s, respectively).

From (4), agent's optimal choices (6) and (7), (11) and the definition of $\bar{h}$, we have

$$h_{t+1}^s = \epsilon C_1 \frac{\left(\bar{\theta} h_t^s - \underline{\theta}\nu(\xi h_t^u + (1-\xi)h_t^s)\right)^{\alpha+\beta}}{\left(1+\nu A(\xi h_t^u + (1-\xi)h_t^s)\right)^{\alpha}} \left(h_t^s\right)^{\mu} \times (\xi h_t^u + (1-\xi)h_t^s)^{\delta}, \tag{12}$$

$$h_{t+1}^u = \epsilon C_1 \frac{\left(\bar{\theta} h_t^u - \underline{\theta}\nu(\xi h_t^u + (1-\xi)h_t^s)\right)^{\alpha+\beta}}{\left(1+\nu A(\xi h_t^u + (1-\xi)h_t^s)\right)^{\alpha}} \left(h_t^u\right)^{\mu} \times (\xi h_t^u + (1-\xi)h_t^s)^{\delta}, \tag{13}$$

with

$$C_1 \equiv \frac{(\lambda+\alpha\gamma)^{\alpha}}{(1+\gamma\beta+\alpha\gamma+\lambda)^{\alpha+\beta}} \left(\frac{\gamma\beta}{\bar{\theta}}\right)^{\beta} A^{\alpha+\beta}.$$

In order to measure inequality, we define the relative human capital of unskilled individuals with respect to skilled individuals in period t as $x_t \equiv h_t^u/h_t^s$. Initial condition on human capital stocks ($h_0^u < h_0^s$) leads us to focus only on x_t lower than or equal to one, i.e. $\in (0, 1]$. If $x = 1$, there is no inequality among agents. And the lower is x, the wider are disparities.

Using (12), (13) and the definition of x_t, we finally obtain the dynamic equation characterizing equilibrium paths:

Definition 1. Given the initial condition $x_0 = h_0^u/h_0^s < 1$, the intertemporal equilibrium is the sequence $x_t \in [0, 1]$ which satisfies, at each t, $x_{t+1} = f(x_t)$, with

$$\begin{cases} f(x_t) = (x_t)^{\mu} \left[\frac{\bar{\theta}x_t - \underline{\theta}\nu(\xi x_t + (1-\xi))}{\bar{\theta} - \underline{\theta}\nu(\xi x_t + (1-\xi))}\right]^{\alpha+\beta} & \text{for} \quad x_t > \underline{x} \\ f(x_t) = 0 & \text{for} \quad x_t \leqslant \underline{x}, \end{cases} \tag{14}$$

with $\underline{x} \equiv \frac{\underline{\theta}\nu(1-\xi)}{\bar{\theta} - \underline{\theta}\nu\xi}$.

Using (12) and (13) with the definition of x_t, we can see that the human capital of skilled agents is always positive, as x_t is lower than one. However, for unskilled households, children's human capital is positive only if x_t is higher than $\underline{x}$ (given in Definition 1). Otherwise, pollution externality is too high: unskilled households' expenditures in their children's health, s_t^u, are not sufficient to guarantee a positive health input and these households are not able to ensure a positive investment in education ($e_t^u = 0$). It follows that the level of human capital of their children tends to zero. It means that this part of the population collapses. Note that to avoid that the economy is always collapsing, $\underline{x}$ needs to be lower than 1, which implies that $\bar{\theta} > \underline{\theta}\nu$. In other words, when pollution is important and costly for health ($\underline{\theta}\nu$ high), parental efforts to keep the environmental health input positive have to be sufficiently efficient ($\bar{\theta}$ high). Otherwise, it would never be possible for unskilled agents to sustain the accumulation of human capital given their financial constraint and this population would finally collapse.

4.1. Long-term states with and without inequality

From Definition 1, we explore the properties of the dynamic equation $f(x_t)$ and deduce the existence of steady state(s) x corresponding to the solutions of the equation $x = f(x)$. Such a steady state corresponds to a long-term equilibrium in which both skilled and unskilled human capital are stationary. This long-term state is characterized as a state with inequality if $x \neq 1$ and as a state without inequality if $x = 1$, meaning that $h^u = h^s$.

Proposition 1. *Under Assumption 1, there always exists a steady state without inequality* $x = 1 \equiv x^E$. *According to a critical threshold* $\hat{\nu} = \frac{\bar{\theta}(1-\alpha-\beta-\mu)}{\underline{\theta}(1-\mu)}$, *we have that*

- *When* $\nu < \hat{\nu}$, *the steady state without inequality* x^E *is locally stable and there also exists at least one steady state with inequality* $\underline{x} < x < 1$, *with the lowest one being unstable.*
- *When* $\nu > \hat{\nu}$, *the steady state without inequality* x^E *is locally unstable and there may also exist none or several steady states with inequality* $\underline{x} < x < 1$. *In the case in which there are several steady states with inequality, the lowest one is unstable while the highest one is stable.*

Proof. See Appendix A.1 ■

Proposition 1 shows that the economy may converge to a long-term state with or without inequality and illustrates the roles of the emission intensity of production (ν), the human capital accumulation weights (α, β and μ) and the environmental health parameters ($\bar{\theta}$ and $\underline{\theta}$) in achieving one situation or the other.

The role of all these parameters on the long-term behavior of the economy is due to the fact that our model captures different channels through which human capital inequality may widen over time. First, we consider the usual divergent forces in human capital accumulation represented in the literature (see, e.g., Tamura, 1991; Glomm and Ravikumar, 1992 or De La Croix and Doepke, 2003), i.e. forces that perpetuate inequality among agents across generations: the intergenerational transmission of human capital within each family and the parental investment in education — whose weights are μ and β, respectively. Indeed, skilled parents have more human capital to bequeath to their children (for example, it would be easier for them to help their children with their homework, or to provide information about graduate schools) and they have also a larger income (as the total wage depends on the level of human capital), enabling them to invest more in education than lower-skilled agents.

Second, we represent an additional divergent force in human capital accumulation that is the environmental health of children — whose weight is α.[7] More precisely, the mechanism occurring in our paper can be described as follows. The higher the pollution (P_t), the lower the children's health (Θ_t^i). It implies that parents need to spend more money to reduce the exposition and vulnerability of their children (s_t^i) and thus, that they are less able to fund the education of their children. Moreover, a lower health decreases the efficiency of human capital accumulation and hence the return on the education investment. Therefore, pollution entails that parents are less able and less willing to invest in education. Finally, as unskilled agents have a lower level of human capital than skilled agents, they have also a lower total wage. Thus, through both channels, they are more affected by this mechanism than skilled agents. This is the case while we do not assume any difference in exposure to pollution between the two kinds of agents.

This new channel is not only adding a divergent force. It is particularly important because it evolves endogenously with pollution. While the literature on human capital inequality usually find that if the sum of all the divergent forces in the human capital accumulation is lower than one, the convergence of human capital among agents in the long run is ensured, this is not

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[7] See Aloi and Tournemaine (2013) for another study considering the negative effect of pollution on human capital accumulation. Note that we depart from this work by considering the possibility for parental expenditures on health and by assuming no difference in the innate skills of children nor in their exposure to pollution. In doing so, we adopt a more general framework and represent an endogenous heterogeneity in terms of vulnerability that is found even for similar exposure.

the case in this paper. The weight of these divergent forces (the usual and the new one) is very important for the dynamics of inequality, but such a convergence is not guaranteed even if their sum $\alpha+\beta+\mu$ is lower than 1 (i.e. Assumption 1).[8] This is due to the effect of pollution on the endogenous environmental health of children Θ_t^i. Without pollution ($\nu = 0$), the growth of individual human capital along the transitional path would always be larger for unskilled agents under Assumption 1, meaning that the gap between agents would be shrinking and there would always be a human capital convergence among agents in the long run.[9] However, with pollution ($\nu > 0$), the growth of individual human capital along the transitional path may be larger or lower for unskilled agents, thus the economy may achieve a long-term state with or without inequality. Therefore pollution, through its negative effect on the health of children, is essential in our model for explaining the dynamics of the economy.

In order to provide details about the different possible cases, we sum up the economic implications of Proposition 1 in the following corollary:

Corollary 1. *Under Assumption 1*

- *When $\nu < \hat{\nu}$, we observe that*
  - *if the initial relative human capital of unskilled agents x_0 is sufficiently high, the economy converges toward a long-term state without inequality.*
  - *if the initial relative human capital of unskilled agents x_0 is too low, the economy will exhibit persistent inequality in the long run. More precisely, the economy*
    - *converges toward a steady state with persistent but constant inequality ($x < 1$)*
    - *or is caught in an inequality trap with steadily rising disparities (i.e. moving asymptotically toward a situation in which inequality is maximum $x = 0$).*
- *When $\nu > \hat{\nu}$, initial inequality always persists across time. The economy*
  - *converges toward a steady state with inequality (relative human capital lower than one)*
  - *or is stuck in the inequality trap ($x = 0$).*

If the pollution intensity and initial inequality are sufficiently low ($\nu < \hat{\nu}$ and x_0 sufficiently high), the economy may converge to a long-term equilibrium without inequality. But in all the other cases, the economy will converge to a long-term state with persistent (or even increasing) inequality.

The emission intensity of production ν favors the transmission of inequality across generations and hence makes the "unequal scenario" more likely. More precisely, with a pollution-intensive production technology (ν too high), the long-term state with equality x^E is unstable, meaning that unskilled agents cannot converge to the same level of human capital as skilled agents. The explanation is twofold. Pollution affects negatively the efficiency of human capital accumulation due to its negative health effect on the children. And pollution prevents parents to invest sufficiently in education as they need to invest in health expenditure to limit the negative effect of pollution. The fact that there is initial inequality makes these effects larger for unskilled households than skilled households. And when the emission intensity of production is high, poor households will never be able to narrow existing disparities — even for very low initial inequality.[10] Therefore, the economy will converge to a long-term state with inequality. In the best scenario, these disparities are persistent but constant in the long run. In the worse scenario, these disparities are steadily increasing over time. This corresponds to an inequality trap, in which the living conditions of the poor agents are constantly deteriorating. The economy is moving asymptotically toward the lower bound of the trap in which the unskilled agents would collapse ($x = 0$), meaning that their level of human capital tends to zero, as do their income, their ability to consume *etc.*[11]

With a low-pollution production technology (ν sufficiently low), the long-term state without inequality is stable, meaning that reaching an equal long-term state is possible. Typically, if initial disparities among agents are sufficiently low in this case, the divergent effect of pollution on human capital accumulation is low enough such that the growth of individual human capital of unskilled agents is larger than the one of skilled agents. Therefore, the gap between them reduces at each generation and there is a convergence in the levels of human capital among the population. However, if initial disparities are too large, the negative effects of pollution on human capital are much larger for unskilled households than for skilled households and the gap between them cannot reduce over time. Thus, the economy will exhibit persistent or increasing disparities.

The second item in Proposition 1 emphasizes that there may exist a critical scenario in which the economy can never escape an inequality trap in which the living conditions of poor agents constantly decline (i.e. a unique steady state that is without inequality but unstable). Further investigations allow to identify a specific condition such that this situation occurs.

Proposition 2. *Under Assumption 1 and the following sufficient condition:*

$$(1-\mu)\bar{\theta}(\bar{\theta}-\underline{\theta}\nu) < (1-\xi)\xi(\alpha+\beta)(\underline{\theta}\nu)^2, \tag{15}$$

there is a unique steady state, which is without inequality $x = 1$ and unstable. Therefore, the economy is caught in the inequality trap for all initial conditions.

Proof. See Appendix A.2 ■

As emphasized after Proposition 1, the larger the weights of the divergent forces in human capital accumulation (captured by α, μ and β), the larger the transmission of inequality. Thus, these parameters make the situation in which the economy is always stuck in the trap more likely. Moreover, Condition (15) holds when ν and/or $\underline{\theta}$ are high enough or when $\bar{\theta}$ is sufficiently low. This implies that health input and education spendings are low because of high pollution damages. In this case, the level of unskilled parental investment is never sufficient to observe a more equal distribution of income in the society: human capital of unskilled offspring is too low to catch up the initial unequal distribution of human capital and the situation of unskilled always deteriorates across time relatively to those of skilled agents.

When condition (15) does not hold, there may exist multiple steady states with several configurations, and typically x^E may be stable or not. In the following proposition, we focus on the latter case, meaning that the economy will converge toward a state in which inequalities remain stable or in which they increase over time, depending on its initial conditions.

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[8] Otherwise ($\alpha+\beta+\mu$ were > 1), it would be impossible to achieve a long-term equilibrium without inequality, and inequality would worsen in all scenarios.

[9] In this case, there is only one steady state, which is without inequality and stable.

[10] Under $\nu > \hat{\nu}$, achieving a long-term state without inequality would only be possible for an economy without initial inequality.

[11] Note that, the economy is moving asymptotically toward this extreme state but cannot be at it, as it would not be bearable.

Proposition 3. *Under Assumption 1 and the following condition*

$$\frac{1-\mu}{\alpha+\beta} + \frac{\ln[1-\mu-2(1-\alpha-\beta-\mu)(1-0.5\xi)]}{\ln 2} > 1 + \frac{\ln[1-\mu-(1-\alpha-\beta-\mu)(1-0.5\xi)]}{\ln 2} \tag{16}$$

there exists a critical threshold $\tilde{\nu} > \hat{\nu}$ such that when $\nu \leqslant \tilde{\nu}$, we have $f(1/2) \geqslant 1/2$. As a result, for $\hat{\nu} < \nu < \tilde{\nu}$, x^E is unstable and there are also multiple steady states with inequality, among which the highest one is stable.

Proof. See Appendix A.3 ■

This proposition identifies sufficient conditions to have a long-term state with inequality ($0 < x < 1$) that is stable. It depends on the parameters $\mu+\beta+\alpha$, ξ and ν. In other words, the divergent forces in human capital formation ($\mu+\beta+\alpha$) should be high such that there is inequality in the long run. The share of unskilled agents in the population (ξ) should also be sufficiently high so that the aggregate pollution and its negative health effects are not too detrimental, hence enabling to avoid widening inequalities. And, in the same way, the emission intensity of production (ν) should not be too low, so that inequality exists in the long run, and not too high to limit the size of the pollution effect on health that increases disparities.

4.2. Numerical illustration

In this section, we analyze numerically the model to illustrate the different possible cases emphasized in Propositions 1 to 3. In this way, we provide further insights into the long-term behavior of the economy.

4.2.1. Calibration

For that, we need to assign values to some parameters of the model. We choose values so that the model fits empirical observations for developed countries. They are summarized in Table 1.

In the literature, the return to schooling in developed countries is estimated to be between 8 and 16% (see Ashenfelter and Krueger, 1994; Psacharopoulos, 1994 or Krueger and Lindahl, 2001). These figures only include an opportunity cost in terms of forgone earnings but not education expenditure. Following De La Croix and Doepke (2003), we assume that an additional year of schooling increases such expenditure by 20%. The resulting elasticity of education ranges from 0.4 to 0.8. Thus, we set the sum of the weights concerning education in human capital accumulation – education spendings and environmental health defining learning abilities – to be 0.6. More precisely, we choose α equal to 0.2 and β equal to 0.4. Consequently, the weight of intergenerational transmission of human capital μ should satisfy our assumption that human capital convergence is not impossible, i.e., $\mu \in [0, 1-\alpha-\beta)$. Thus, we consider $\mu = 0.3$, which matches the values identified in the empirical literature, i.e. between 0.2 and 0.45 (see, e.g., Dearden et al., 1997 or Black et al., 2005).

Concerning children's health parameters, we need to choose values for $\bar{\theta}$ and $\underline{\theta}$. There is no estimation for these parameters in the literature but we need to ensure that $\underline{x} < 1$ so that the economy is not always collapsing. It implies that $\bar{\theta} > \nu\underline{\theta}$. Thus, we assume that $\bar{\theta}$ and $\underline{\theta}$ are equal to 0.6 and 0.4, respectively. And we consider all possible values of ν, which is the key parameter of our model, i.e. $\nu \in [0, 1.5)$.

We assign values to the preference for children's human capital γ and the preference for children's environmental health λ to fit the share of education expenditure in GDP at equilibrium in developed countries (i.e., between 4 and 9%)[12]. In the model, this share depends on ν, which is let free in the model. We find that the range of possible values for this share of education expenditure in GDP corresponds to the real values for γ and λ equal to 0.35.[13]

Finally, for simplicity and neutrality purposes, we assume that the two types of agents have equivalent sizes (i.e. $\xi = 0.5$).

4.2.2. Illustration of the long-term behaviors of the economy

The study of the existence and dynamics of the steady states in the calibrated economy gives the following result and is represented in Figs. 1 and 2 for different values of $\nu \in [0, 1.5)$.

Numerical result 1. *(i) When $0 < \nu < \hat{\nu}$, there are two steady states: a steady state without inequality that is stable and a steady state with inequality that is unstable. Thus, the economy is stuck in the inequality trap for high initial disparities (x_0 lower than the steady state with inequality), but can converge to a long-term equilibrium without inequality otherwise.*
(ii) When $\nu > \hat{\nu}$, there is a unique steady state, which is without inequality and unstable. Therefore, the economy is stuck in the inequality trap for all levels of initial disparities $x_0 < 1$.

As explained previously, without pollution ($\nu = 0$), the economy would always converge to a long-term equilibrium without inequality, as it is stable and the unique positive equilibrium (left panel of Fig. 1). However, in the presence of pollution ($\nu > 0$), inequality may persist in the long run. More precisely, we find that there always exists an inequality trap in which disparities among households persistently grow. In this calibrated economy, the threshold value $\hat{\nu}$ corresponds to 0.2143. As illustrated on the right panel of Fig. 1, when $0 < \nu < 0.2143$, the economy is stuck in the trap for high initial disparities but can converge to the long-term state without inequality otherwise. However, when $\nu > 0.2143$, the long-term equilibrium without inequality is the only one left and becomes unstable, meaning that the economy is stuck in an inequality trap whatever its initial condition $x_0 \in (0, 1)$. As represented in Fig. 2, if there is inequality initially – even very few –, the economy will exhibit inequality that widens at each generation until the lower-skilled households collapse. Moreover, as ν increases, $f(x_t)$ goes to the right. Thus, the larger the pollution intensity of production ν, the faster the economy collapses ($f(x_t)$ is equal to 0 for a larger set of x).

For robustness, we test the model for a large set of parameters. In most cases, we find that the economy is either stuck in the inequality trap or converges to the long-term equilibrium without inequality for low value of pollution intensity, as summarized in the Numerical result 1. However, the value of $\hat{\nu}$ varies according to the weights of the divergent forces in human capital accumulation (α, β and μ). The larger they are, the larger the size of the inequality trap, as explained after Proposition 1. This key threshold also depends on the parameters in children's environmental health. The larger the efficiency of health expenditure $\bar{\theta}$ relatively to the weight of pollution in environmental health $\underline{\theta}$, the lower is the size of the inequality trap. This is because inequality is due to the health effects of pollution and when $\bar{\theta}$ is relatively high with respect to $\underline{\theta}$, it implies that individuals are relatively less vulnerable to pollution and health expenditure enables relatively easily to overcome the negative effect of pollution. For example, for $\bar{\theta} = 0.7$ and $\underline{\theta} = 0.2$ and all other parameters being equal, the threshold $\hat{\nu}$ - above which the long-term equilibrium without inequality is unstable — becomes 0.5. As in the previous calibration, there are two long-term equilibria for small emission intensity,

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[12] See OECD (2020), Education spending (indicator). doi: 10.1787/ca274bac-en (Accessed on 14 May 2020).

[13] We do not need to calibrate these preferences to represent the long-term behaviors of the economy, but it will be useful to examine the effect of the policy in Section 5.

Table 1
Description of the model parameters.

Parameter	Description	Calibrated value
α	Weight of environmental health in human capital accumulation	0.2
β	Weight of education in human capital accumulation	0.4
μ	Weight of intergenerational transmission in human capital accumulation	0.3
$\bar{\theta}$	Weight of health expenditure in environmental health	0.6
$\underline{\theta}$	Weight of pollution in environmental health	0.4
ν	Emission rate of production	[0,1.5]
γ	Preference for children's human capital	0.35
λ	Preference for children's environmental health	0.35
ξ	Share of unskilled individuals in each cohort	0.5

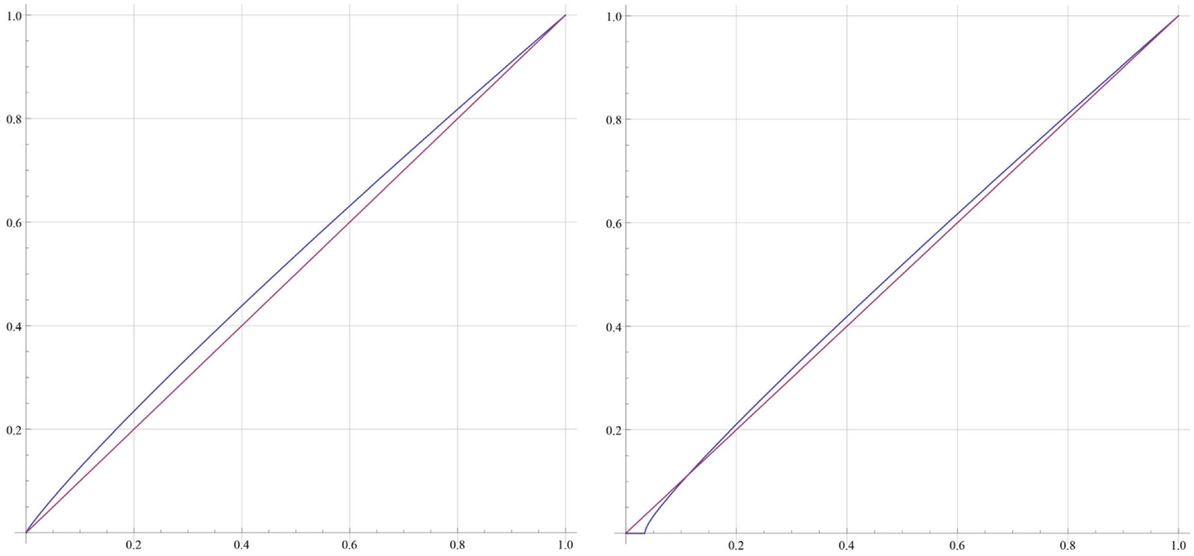

Fig. 1. Dynamics for $\nu = 0$ (left panel) and $\nu = 0.1$ (right panel), with x_t on the X-axis and x_{t+1} on the Y-axis. The blue curve is the dynamic equation characterizing equilibrium paths $x_{t+1} = f(x_t)$, while the pink curve is the first bisector $x_{t+1} = x_t$.

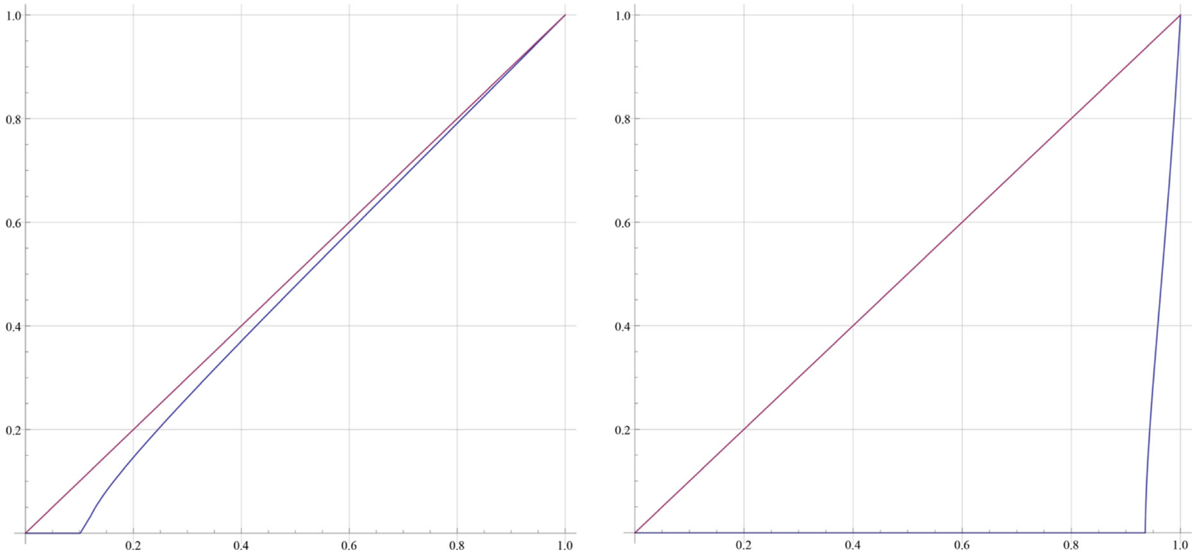

Fig. 2. Dynamics for $\nu = 0.3$ (left panel) and $\nu = 1.45$ (right panel), with x_t on the X-axis and x_{t+1} on the Y-axis. The blue curve is the dynamic equation characterizing equilibrium paths $x_{t+1} = f(x_t)$, while the pink curve is the first bisector $x_{t+1} = x_t$.

i.e. $\nu \in (0, 0.5)$: the one without inequality is stable, while the equilibrium with inequality is unstable and represents the upper bound of the inequality trap. In this parameter range, the larger the emission rate, the larger the size of the inequality trap. The economy exhibits the same long-term behaviors as previously but the trap is smaller for a given value of ν. And for $\nu > \hat{\nu}$ (here 0.5), there is only one equilibrium – the long-term state without inequality – but it is unstable, meaning that the economy is stuck in the inequality trap for all levels of initial disparities. Therefore, the results with these parameters are the same as previously and the inequality trap – albeit of a smaller size – still exists. Indeed, even if the weight of health expenditure in children's health $\bar{\theta}$ is much larger than the weight of pollution $\underline{\theta}$, meaning that it is relatively easy to reduce the damaging health effect of pollution,

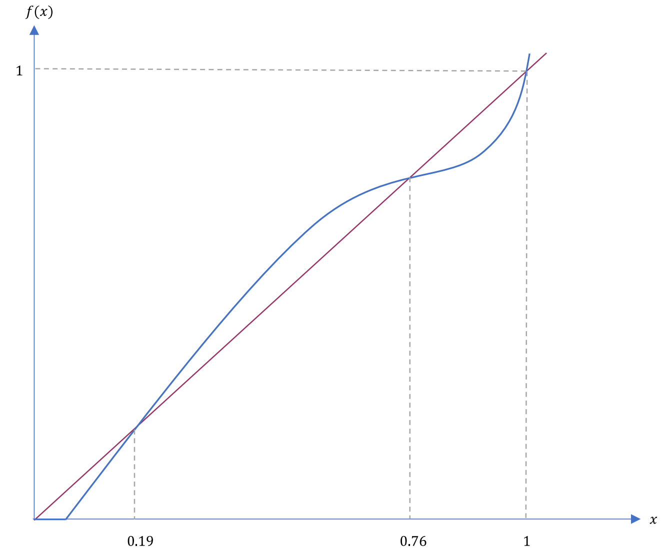

Fig. 3. Dynamics for the calibrated values summarized in Table 1 and $\xi = 0.8$ and $\nu = 0.23$.

unskilled agents are still not able to accumulate human capital and hence to survive when the pollution intensity is too high.

For some specific parameters values, we can also find a stable long-term state with inequality, as emphasized in Proposition 3 and illustrated in Fig. 3. This equilibrium implies that the economy may achieve a state with persistent but constant inequality in the long run. However, we need to note that when we observe such a steady-state, there are also an equilibrium without inequality that is unstable and a lower unstable equilibrium with inequality. Thus, the inequality trap still exists. The economy may converge to a state with constant inequality in the long run, but only for sufficiently low initial disparities. As commented after Proposition 3, this third long-term state is found under some specific conditions implying that disparities exist in the long run but are not widening across time. In other words, pollution and its health effects need to be intermediary (neither too high nor too small) so that the economy may exhibit constant disparities in the long run when the initial level of inequality is low.

5. Policy implications

Pollution being responsible for the persistence of inequality through its effects on the health of children, we want to examine how policies focusing on environmental health may address this issue. Therefore, this section is devoted to the study of the implications of an environmental policy and of a health policy. A natural approach to tackle the issue of human capital inequality would be to consider an education policy or a monetary transfer. However, human capital development is multidimensional and calls for policy actions beyond traditional education supports, as underlined in the Human Development Report (2019). And, more importantly, our previous results suggest that such policies could not be sufficient to address inequality. Indeed, a lower health decreases the efficiency of human capital accumulation and hence the return on the education investment. Because of pollution, parents are less able, but also less willing to invest in education and prefer to focus on health expenditures.[14]

After providing details about the policy tools considered, we examine the role of an environmental policy in achieving a long-term state without inequality. We also study the effect of a policy mix with an environmental policy – aiming at reducing the source of inequality – and a health policy — to lessen the mechanism through which pollution generates inequality. For each policy, we provide analytical results that we illustrate numerically to provide a more comprehensive overview of the different scenarios.

5.1. *The government*

We assume that the government implements two taxes on production (which is the source of pollution). An environmental tax τ_p is implemented to fund pollution abatement M_t, while a health tax τ_s is used to provide a subsidy on health spending σ_t.[15] These taxes satisfy that τ_p, τ_s and $\tau_p + \tau_s$ are all $\in [0, 1)$.

The policy is summarized by two instruments, τ_p and τ_s while the amount of maintenance M_t and the rate of subsidy σ_t are endogenously determined to satisfy the public budgets. The government balances its budget such that

$$\begin{cases} M_t = \tau_p Y_t, \\ \sigma_t((1-\xi)s_t^s + \xi s_t^u) = \tau_s Y_t. \end{cases} \tag{17}$$

With these policies, pollution becomes

$$P_t = \nu Y_t - M_t = (\nu - \tau_p) Y_t = (\nu - \tau_p) A \bar{h}_t, \tag{18}$$

Note that, based on the new law of motion of pollution (18), we assume the following condition to be true in order to ensure that the aggregate economic activity is associated with a net pollution flow that is always positive[16]:

Assumption 2. $\tau_p < \max(\nu, 1)$.

With policy, the budget constraint for an adult of type i is now given by

$$c_t^i + e_t^i + s_t^i(1 - \sigma_t) = w_t h_t^i, \tag{19}$$

and taxes reduce the equilibrium wage w_t which is equal to $A(1 - \tau_p - \tau_s)$. The details of all the new equations for optimal choices and dynamics, integrating the policy tools, are reported in Appendix A.4.

In presence of policy intervention, Definition 1 that summarizes the dynamic equation characterizing equilibrium paths becomes

Definition 2. Given the initial condition $x_0 = h_0^u / h_0^s < 1$, the intertemporal equilibrium is the sequence $x_t \in [0, 1]$ which satisfies, at each t, $x_{t+1} = f(x_t)$, with

$$\begin{cases} f(x_t) = (x_t)^{\mu} \\ \qquad \times \left[\frac{(1-\tau_p-\tau_s)\bar{\theta} x_t - (1-\sigma(\tau_p,\tau_s))\underline{\theta}(\nu-\tau_p)(\xi x_t + (1-\xi))}{\bar{\theta}(1-\tau_p-\tau_s) - (1-\sigma(\tau_p,\tau_s))\underline{\theta}(\nu-\tau_p)(\xi x_t + (1-\xi))} \right]^{\alpha+\beta} & \text{for} \quad x_t > \underline{x} \\ f(x_t) = 0 & \text{for} \quad x_t \leqslant \underline{x}, \end{cases} \tag{20}$$

with $\underline{x} \equiv \frac{(1-\sigma(\tau_p,\tau_s))\underline{\theta}(\nu-\tau_p)(1-\xi)}{\bar{\theta}(1-\tau_p-\tau_s) - \underline{\theta}(1-\sigma(\tau_p,\tau_s))(\nu-\tau_p)\xi}$.

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[14] This result is in line with Castello-Climent and Domenech (2008) and Constant (2019) who emphasize a similar mechanism for monetary transfers.

[15] Note that we consider two taxes, as Raffin and Seegmuller (2014), in order to treat the two types of policies independently and to show easily the effect of each instrument.

[16] Otherwise, when $\nu < 1$, there would exist a policy $\tau_p = \nu$ allowing to remove all pollution in the economy and a policy $\tau_p > \nu$ such that the net flow of pollution would be negative. Both cases are highly unrealistic, that is why we do not consider them.

Note that the term $\sigma(\tau_p, \tau_s)$ in Definition 2 is the subsidy that balances the public budget at the equilibrium (17). It depends positively on the two taxes because of several effects. First, because both taxes reduce agents' available income and hence their health expenditure. As the government subsidies a share of this spending, the cost goes down when spending is lower, so the subsidy that balances the budget is higher. In addition, τ_s directly contributes to the budget allocated to health expenditure. These two channels explain the positive effect of τ_s. The tax τ_p has also a second positive effect on σ because it reduces total pollution and hence improves health. Agents decrease their contribution to health input when pollution is lower, which reduces the overall cost of the health policy and allows the government to fix a higher subsidy rate.

To provide some intuitions about the effects of the policy instruments on the dynamics of the economy and on the evolution of inequalities, we present in the following lemma the effect of τ_p and τ_s on the dynamic equation $f(x)$.

Lemma 1. *Effect of τ_p and τ_s on the dynamic equation $f(x)$ when $x_t > \underline{x}$:*

$$Sign\ \ \mathrm{d}f(x_t) = (1-x_t)\left[Sign\frac{\partial f(x_t)}{\partial \tau_p}\mathrm{d}\tau_p + (\nu-\tau_p)Sign\frac{\partial f(x_t)}{\partial \tau_s}\mathrm{d}\tau_s\right], \tag{21}$$

with

$$Sign\frac{\partial f(x_t)}{\partial \tau_p} = -Sign\frac{\partial \underline{x}}{\partial \tau_p}$$

$$= Sign\left[(1-\tau_s-\nu)(1-\sigma) + \frac{\partial \sigma}{\partial \tau_p}(\nu-\tau_p)(1-\tau_p-\tau_s)\right]$$

and

$$Sign\frac{\partial f(x_t)}{\partial \tau_s} = -Sign\frac{\partial \underline{x}}{\partial \tau_s} = Sign\left[(1-\tau_s-\tau_p)\frac{\partial \sigma}{\partial \tau_s} - (1-\sigma)\right].$$

Proof. Directly obtained by differentiating $f(x)$, given in (20), with respect to τ_p and τ_s. ■

5.2. Environmental policy

As disparities are widening because of pollution in our model, we examine first if the environmental policy alone is sufficient to remove inequalities. Thus, the policy we consider in this subsection only consists in providing public environmental maintenance by taxing production (there is no health policy $\tau_s = \sigma = 0$).

We start by examining how the environmental policy affects the dynamic equation characterizing the long-term state(s) of the economy $f(x)$. As we can see in Lemma 1 when $\tau_s = \sigma = 0$, the environmental tax τ_p has a positive (resp. negative) effect on $f(x_t)$ and a negative (resp. positive) effect on the threshold $\underline{x}$ when $\nu < 1$ (resp. $\nu > 1$).

To have a more accurate view about the effects of the environmental policy on the economy, we pay a particular attention to how the critical threshold in terms of emission intensity $\hat{\nu}$ evolves with the policy. Indeed, examining the position of ν relative to this threshold provides important information about the long-term behaviors of the economy and their properties in terms of inequality. Using details provided in Appendix A.3, we find that it turns into

$$\hat{\nu}_p \equiv \frac{\bar{\theta}(1-\tau_p)(1-\alpha-\beta-\mu)}{\underline{\theta}(1-\mu)} + \tau_p. \tag{22}$$

Therefore, the long-term state without inequality $x = 1$ is stable (resp. unstable) when $\nu < \hat{\nu}_p$ (resp. $\nu > \hat{\nu}_p$). To show how the policy affects this threshold, we analyze the differential of $\hat{\nu}_p$ with respect to policy instruments τ_p:

$$\mathrm{d}\hat{\nu}_p = \underbrace{\mathrm{d}\tau_p}_{\text{Environmental effect}} - \underbrace{\frac{\bar{\theta}(1-\alpha-\beta-\mu)}{\underline{\theta}(1-\mu)}\mathrm{d}\tau_p}_{\text{Income effect}}.$$

The environmental policy can make the stability condition of the equal long-term state more or less restrictive. The tax τ_p generates two competing effects on the critical threshold $\hat{\nu}_p$: a positive environmental effect and a negative income effect. On the one hand, the revenue from the environmental tax is recycled in an investment in environmental maintenance, which reduces pollution. Thus, the tax enables to lower the source of the widening of inequalities, and hence to favor the human capital convergence among households. On the other hand, the tax has a negative effect on agents' available income, which means that parents are less able to invest in their children's health and in their education. As the income of low-skilled agents is lower than the one of high-skilled, the former are even more affected. Thus, the tax also fosters disparities among households through this effect.

A necessary condition to have an environmental policy that favors the stability of the equal steady state is that the threshold $\hat{\nu}_p$ increases with τ_p:

$$\frac{\mathrm{d}\hat{\nu}_p}{\mathrm{d}\tau_p} > 0 \quad \Leftrightarrow \quad \underline{\theta}(1-\mu) > \bar{\theta}(1-\alpha-\beta-\mu) \quad \Leftrightarrow \quad \hat{\nu} < 1 \tag{23}$$

Therefore, the effect of the environmental policy on the stability properties of the equal long-term state x^E depends on the weights of the divergence forces in human capital accumulation (α, β and μ), on the efficiency of health expenditure $\bar{\theta}$ and on the weight of pollution in health $\underline{\theta}$. As we can see, this is directly linked to the threshold in terms of the emission intensity of production without policy $\hat{\nu}$ (see, Proposition 1). The condition (23) implies that $\hat{\nu}$ is lower than 1, which makes long-term inequality true for a large set of emission intensity. In other words, the impact of pollution on disparities should be sufficiently large (relatively high divergent forces and health effect of pollution and relatively low efficiency of health expenditure) so that the environmental effect of the tax is higher than its negative income effect. In this case, the tax on pollution increases the threshold and makes the convergence toward the equilibrium without inequality more likely. On the contrary, when (23) does not hold, $\hat{\nu}$ is larger than 1, meaning that the set of emission intensity such that the long-term state without inequality is stable is large. In this case, the effect of pollution on disparities is relatively low. Therefore, the positive environmental effect of the environmental policy is relatively low with respect to the negative income effect, and the ability of the policy to decrease inequality is poor.

The effects of the environmental policy on the dynamics of the economy largely depends on the characteristics of the economy before the implementation of the public instruments. In particular, it is important to distinguish between two cases: the case in which, without public intervention, the economy is characterized by a stable long-term state without inequality x^E and the reverse case in which this state is unstable. Based on the elements previously presented, we highlight all the possible scenarios in the following proposition.

Proposition 4. *Under Assumptions 1 and 2,*

1. *If $\nu < \hat{\nu} < 1$, the state x^E is stable without policy and stays stable for all $\tau_p \in (0, \nu)$. Moreover, an increase in τ_p makes $f(x)$ shift upward and lowers $\underline{x}$. It decreases the value of the lowest state with inequality that is unstable, i.e. reduces the size of the inequality trap.*

2. *If $\hat{\nu} < \nu < 1$, the state x^E is initially unstable and the policy can change this situation. An increase in τ_p makes $f(x)$ move upward and lowers $\underline{x}$. Thus, if there are multiple steady states, a higher τ_p reduces the size of the inequality trap. Moreover, there exists a threshold $\hat{\tau}_p < \nu$ such that when*

$$\tau_p > \frac{\nu\underline{\theta}(1-\mu) - \bar{\theta}(1-\alpha-\beta-\mu)}{\underline{\theta}(1-\mu) - \bar{\theta}(1-\alpha-\beta-\mu)} \equiv \hat{\tau}_p \ ,$$

   the environmental policy makes x^E stable (i.e., $\hat{\nu}_p > \nu$).
3. *If $\nu < 1 < \hat{\nu}$, the state x^E is initially stable and stays stable for all $\tau_p \in (0, \nu)$ $(\nu < \hat{\nu}_p)$. Indeed, $\frac{\mathrm{d}\hat{\nu}_p}{\mathrm{d}\tau_p} < 0$ but $\hat{\nu}_p > 1$ $\forall \tau_p \in (0, \nu)$. Moreover, an increase in τ_p makes $f(x)$ shift upward and lowers $\underline{x}$. It decreases the value of the lowest state with inequality that is unstable, i.e. reduces the size of the inequality trap.*
4. *If $1 < \nu < \hat{\nu}$, the state x^E is initially stable. An increase in τ_p makes $f(x)$ move downward and increases $\underline{x}$. Thus, it increases the value of the lowest state with inequality that is unstable, i.e. increases the size of the inequality trap. Moreover, there exists a threshold $\hat{\tau}_{p2} < 1$ such that when*

$$\tau_p > \frac{\bar{\theta}(1-\alpha-\beta-\mu) - \nu\underline{\theta}(1-\mu)}{\bar{\theta}(1-\alpha-\beta-\mu) - \underline{\theta}(1-\mu)} \equiv \hat{\tau}_{p2} \ ,$$

   the environmental policy makes x^E unstable (i.e., $\hat{\nu}_p < \nu$).
5. *If $\hat{\nu} < 1 < \nu$, the state x^E is initially unstable and stays unstable for all $\tau_p \in (0, 1)$, because even if $\hat{\nu} < 1$, $\hat{\tau}_p$ is always higher than 100%. Moreover, an increase in τ_p moves $f(x)$ downward and increases $\underline{x}$. Thus, if there are multiple steady states, a higher τ_p increases the size of the inequality trap.*
6. *If $1 < \hat{\nu} < \nu$, the state x^E is initially unstable and stays unstable for all $\tau_p \in (0, 1)$. Moreover, an increase in τ_p makes $f(x)$ shift downward and increases $\underline{x}$. Thus, if there are multiple steady states, a higher τ_p increases the size of the inequality trap.*

Proposition 4 identifies different situations in which the environmental policy may reduce or increase inequalities. In order to provide further insights on these results, we provide a numerical illustration of them. For that, we use the values reported in Table 1 for the parameters μ, β, α and ξ. Concerning the emission rate of production (ν) and the weights of health expenditure and pollution in the child environmental health ($\bar{\theta}$ and $\underline{\theta}$ respectively), we have seen that they are determining for the policy effects and that there is no empirical counterpart for these parameters. Therefore, we set their values in order to illustrate all the different possible configurations given in Proposition 4. We summarize the cases 1 to 6 of Proposition 4 in the following four scenarios.

Numerical result 2.

(*a*) *If $\nu < \min(\hat{\nu}, 1)$, an increase in the environmental tax reduces the size of the inequality trap, while the long-term state without inequality remains stable. Thus, the environmental policy can enable an economy to escape from the inequality trap.*

(*b*) *If $\hat{\nu} < \nu < 1$, an increase in the environmental tax is always able to make the long-term state without inequality stable when $\tau_p > \hat{\tau}_p$. Thus, the policy can allow the economy to converge to this state as long as its initial disparities are sufficiently low.*

(*c*) *If $1 < \nu < \hat{\nu}$, an increase in the environmental tax increases the size of the inequality trap and when $\tau_p > \hat{\tau}_{p2}$ it even makes the long-term state without inequality unstable. Thus, the policy favors inequality and can make the human capital convergence among agents impossible.*

(*d*) *If $\max(\hat{\nu}, 1) < \nu$, the environmental policy is not able to make the long-term state without inequality stable. Moreover, an increase in the environmental tax increases $\underline{x}$, so that the economy collapses more quickly.*

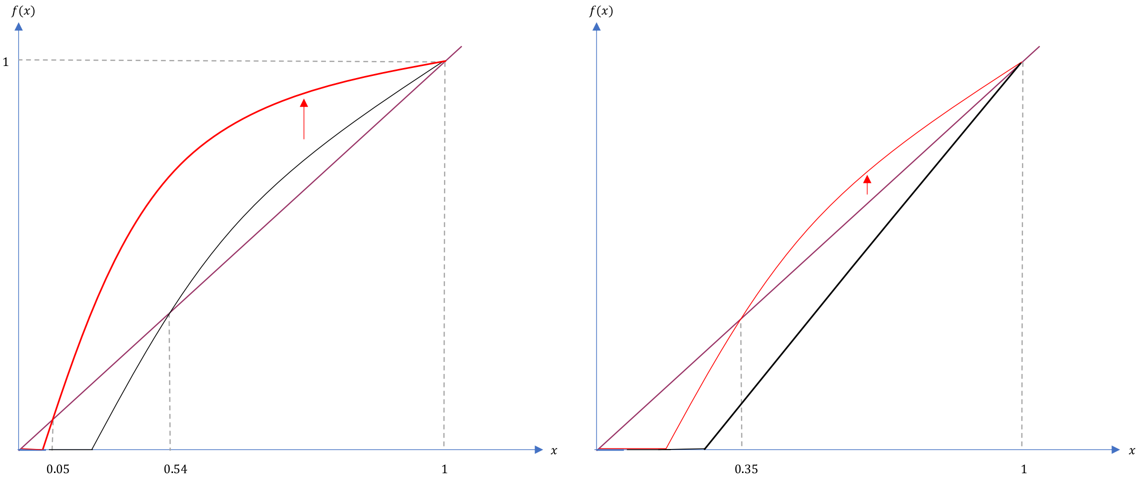
We illustrate the four scenarios of the Numerical result 2 in Fig. 4. In (a), while the economy is stuck in the inequality trap for $x_0 \in (0, 0.54]$ without policy (black curve), an environmental policy $\tau_p = 0.15$ (red curve) significantly reduces the size of the trap to $x_0 \in (0, 0.05]$. Thus, the economy stays caught in the inequality trap despite the policy only if initial disparities are very wide. In (b), while there is always inequality in the long run without policy (black curve), an environmental tax $\tau_p = 0.15 > \hat{\tau}_p$ enables the economy to escape from the trap and to converge to a long-term equilibrium without inequality for all $x_0 > 0.35$ (red curve). To illustrate the case (c), we have to consider a spread sufficiently high between $\bar{\theta}$ and $\underline{\theta}$ such that, despite a high value for pollution intensity ($\nu > 1$), the economy is still characterized by a stable long-term state x^E without policy. In this case, the economy converges to a long-term state without inequality for $x_0 > 0.63$ without policy (black curve), but is stuck for all $x_0 < 1$ with an environmental policy $\tau_p = 0.3$ (red curve). Finally, for the last case, the policy does not change the number nor the configuration of the long-term equilibria, but implies that the economy collapses faster.

Therefore, the environmental policy can be a useful tool to address the inequality issue (cases (a) and (b)). The policy reduces the size of the inequality trap and can even remove the troublesome situation in which the economy cannot converge to the long-term state without inequality whatever its initial disparities (case (b)). Thus, the environmental policy enables an economy to escape from the trap and to converge to a long-term equilibrium without inequality, but only if the emission intensity of production is sufficiently low ($\nu < 1$) and if the level of inequality is not too high.

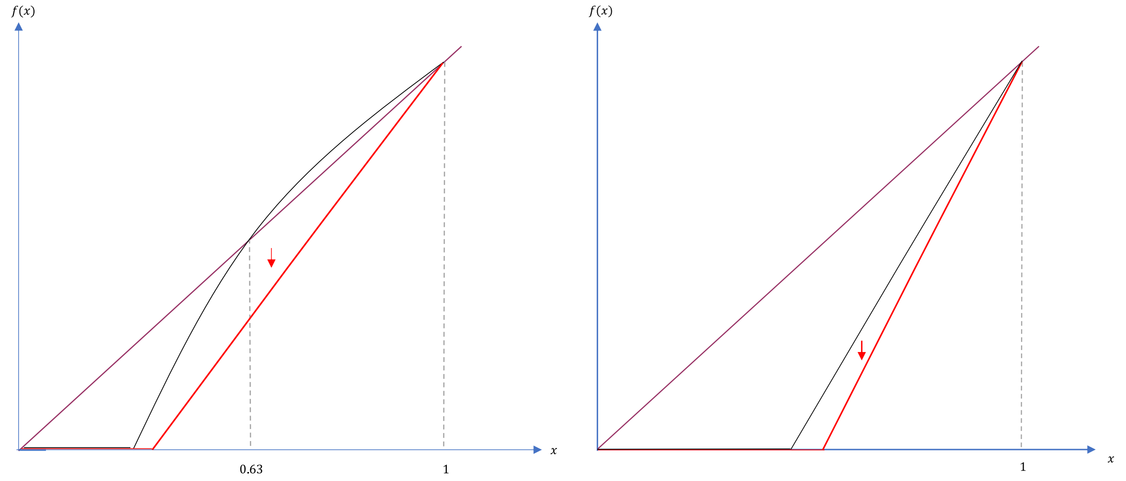
If disparities are too wide before the policy is implemented, the environmental policy is not sufficient to compensate the health gap and hence the education gap, meaning that inequalities continue to grow over time despite the policy (cases of an economy below the upper bound of the trap in (a) and (b)).

If the emission intensity of production is too high ($\nu > 1$), the policy is not sufficient and may even make the inequality issue worse (cases (c) and (d)). Indeed, the policy can be really damaging by increasing the size of the inequality trap, accelerating the collapse or making the long-term state without inequality unstable. This is due to the fact that the policy generates two competing effects: the positive effect through the improvement of the environment, and hence of children's health, and the negative effect on households' income. If the emission intensity is too high, the gap between emissions and maintenance is huge, meaning that the required improvement in the environment and hence the required tax to compensate are very high. However, the efficiency of the environmental policy is limited ($\tau_p < 1$) and the larger is the tax, the larger is the negative income effect. Therefore, when the emission intensity is too high, the negative income effect dominates the positive environmental effect. Poor households benefit from the improvement in their children's health, but are even more affected by the negative effect of the tax on their income limiting their ability to invest in education and health. Thus, implementing or tightening the environmental policy reinforces inequality in this case.

Given the limits of the environmental policy, we wonder if a policy mix with a preventive action – through the reduction of pollution – and a curative action – through a subsidy to health expenditure – could be more efficient. Note that we combine these two instruments rather than studying only the latter because pollution is the source of the problem, but its effect goes



(a) $\nu = 0.2,\ \bar{\theta} = 0.6,\ \underline{\theta} = 0.4,\ \tau_p = 0.15$ (b) $\nu = 0.3,\ \bar{\theta} = 0.6,\ \underline{\theta} = 0.4,\ \tau_p = 0.15$



(c) $\nu = 1.1,\ \bar{\theta} = 0.8,\ \underline{\theta} = 0.1,\ \tau_p = 0.3$ (d) $\nu = 1.2,\ \bar{\theta} = 0.6,\ \underline{\theta} = 0.4,\ \tau_p = 0.15$

Fig. 4. Effect of the environmental tax. Black curve: economy without policy, Red curve: economy with policy.

through children's health and hence could be alleviated through health spendings.[17]

5.3. Policy mix

In this section, we consider both instruments. To identify the channels though which the policy mix can affect inequalities, we first examine the critical threshold of ν over which the equal state x^E is unstable. With both instruments, it satisfies the following equality:

$$\nu = \frac{\bar{\theta}(1-\tau_p-\tau_s)(1-\alpha-\beta-\mu)}{\underline{\theta}(1-\sigma(\tau_p,\tau_s,\nu))(1-\mu)} + \tau_p, \tag{24}$$

with $\sigma(\tau_p, \tau_s, \nu)$, the solution of the following equation:

$$\begin{aligned}\sigma(\lambda+\alpha\gamma)\bar{\theta}(1-\tau_p-\tau_s) = (1-\sigma)\big[&\tau_s\bar{\theta}(1+\gamma\beta+\lambda+\alpha\gamma)\\ &-\sigma\underline{\theta}(1+\gamma\beta)(\nu-\tau_p)\big].\end{aligned} \tag{25}$$

The term on the right hand side is decreasing in ν meaning that the equilibrium value for σ decreases with ν as well. As $\partial\sigma(\tau_p,\tau_s,\nu)/\partial\nu < 0$, it is clear that there exists a unique value $\hat{\nu}_m$ that is solution of (24). The steady state x^E is stable if we have:

$$\nu < \hat{\nu}_m, \tag{26}$$

with

$$\hat{\nu}_m \equiv Sol\left\{\frac{\bar{\theta}(1-\tau_p-\tau_s)(1-\alpha-\beta-\mu)}{\underline{\theta}(1-\sigma(\tau_p,\tau_s,\nu))(1-\mu)} + \tau_p - \nu = 0\right\}.$$

Therefore, a policy mix (τ_p, τ_s) is able to make the long-term state without inequality stable if it satisfies $\nu < \hat{\nu}_m$. In order to analyze more precisely the effects of such a policy, we examine the

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[17] We leave aside the cases in which the tax on pollution is not used because we consider that preventive action, consisting in fighting against the source of inequality issues, is the most meaningful. Moreover, omitting this policy instrument seems unreasonable given the numerous other negative effects of pollution on welfare (not all considered here).

differential of $\hat{\nu}_m$ with respect to the policy instruments τ_p and τ_s:

$$\mathrm{d}\hat{\nu}_m\left(1-(1-\tau_p-\tau_s)\tfrac{\partial\sigma}{\partial\nu}\right) = \underbrace{\mathrm{d}\tau_p}_{\text{Environmental effect}} + \frac{\bar{\theta}(1-\alpha-\beta-\mu)}{\underline{\theta}(1-\mu)(1-\sigma(\tau_p,\tau_s))^2}\left[(1-\tau_p-\tau_s)\underbrace{\left(\frac{\partial\sigma}{\partial\tau_p}\mathrm{d}\tau_p+\frac{\partial\sigma}{\partial\tau_s}\mathrm{d}\tau_s\right)}_{\text{Health effect}} - (1-\sigma(\tau_p,\tau_s))\underbrace{\left(\mathrm{d}\tau_p+\mathrm{d}\tau_s\right)}_{\text{Income effect}}\right]. \tag{27}$$

As the environmental policy, the health policy can make the stability condition more or less restrictive. Indeed, τ_s generates competing effects on the critical threshold $\hat{\nu}_m$. The tax τ_s leads to a fall in agents' available income that affects even more poor individuals, while the subsidy on health expenditure favors the human capital convergence among households. Moreover, there are interactions between health and environmental instruments. The effects of each policy depend on the other policy. The introduction of a health policy amplifies the negative income effect of the environmental policy. A same variation in the environmental tax $\mathrm{d}\tau_p$ generates a larger negative income effect when health is subsidized ($\mathrm{d}\tau_p/(1-\sigma)$). Similarly, the health policy generates a direct positive effect through subsidy, whose magnitude depends on the environmental policy. Indeed, the environmental tax directly contributes to the public budget, which allows to increase the amount of subsidy on health $\left(\frac{\partial\sigma}{\partial\tau_p}\mathrm{d}\tau_p > 0\right)$. In addition, as the environmental tax improves health input (Θ) by reducing the stock of pollution, it leads to a decrease in the amount of private spending allocated to environmental health (s). Public expenditure for health being a share of private spending, it relaxes the public budget constraint and allows to increase the rate of subsidy on health expenditure. When private health spending is subsided by public authorities, the convergence of agents' human capital in the long run is favored. As a result, the higher the pollution tax, the higher the subsidy and hence the more likely the economy achieves a long-term state without inequality.

The channels through which the policy tools affect inequalities are thus multiple and interact between each others. This is also assessed through equation (21) in Lemma 1, as we see that this policy mix leads to several competing effects on the dynamical equation $f(x_t)$. How does the subsidy respond to tax variations is determining (i.e., the values of $\partial\sigma/\partial\tau_p$ and $\partial\sigma/\partial\tau_s$). Moreover, the equilibrium subsidy being dependent on all the parameters of the model (see (25)), it makes difficult to identify the net consequences of such combination of instruments. Nonetheless, we identify sufficient conditions such that the policy mix can be an efficient option to address the inequality issue. This is the purpose of the following proposition.

Proposition 5. *Under Assumptions 1 and 2 and when $\bar{\theta}/\underline{\theta}$ is sufficiently high, there exists a combination of health and environmental policies (τ_p, τ_s) moving $f(x)$ up and $\underline{x}$ down, hence decreasing the size of the inequality trap in the presence of multiple steady states,*

- *when $\nu < 1$, as the environmental policy does.*
- *when $1 < \nu < 1 + \frac{1+\gamma\beta}{\lambda+\alpha\gamma}$, while the environmental policy does not, if with $\tau_s \geqslant \frac{(\lambda+\alpha\gamma)(\nu-1)}{1+\gamma\beta}$.*

Proof. See Appendix A.5 ■

The conditions presented in Proposition 5 ($\bar{\theta}/\underline{\theta}$ high enough and $\nu < 1+\frac{1+\gamma\beta}{\lambda+\alpha\gamma}$) indicate that health expenditure is sufficiently efficient with respect to the detrimental effect of pollution and that the education and health of children are sufficiently valued by parents. They imply that both policy instruments, when implemented together, can have a positive effect on the dynamical equation $f(x_t)$, so that they may reduce inequality. The first condition ($\bar{\theta}/\underline{\theta}$ high enough) ensures that the health policy has a net positive effect on dynamical equation $f(x_t)$ for all possible levels of policy instruments. Combining this condition with the second one ($\nu < 1+\frac{1+\gamma\beta}{\lambda+\alpha\gamma}$) ensures that the environmental tax can also have a net positive effect on dynamical equation $f(x_t)$. This property is observed for all possible levels of policy instruments when $\nu < 1$, while when $\nu > 1$ this is guaranteed when τ_s is high enough ($\tau_s \geqslant \frac{(\lambda+\alpha\gamma)(\nu-1)}{1+\gamma\beta} > 0$) because the environmental policy alone is not efficient (as emphasized in the previous subsection).

Thereafter, we illustrate numerically the potential effects of the policy mix. As previously, we calibrate the parameters μ, β, α, λ, γ and ξ using Table 1 and ν, $\bar{\theta}$ and $\underline{\theta}$ to represent the different relevant scenarios. However, we focus on cases in which the economy cannot achieve a long-term state without inequality (i.e. x^E is unstable) if public authority does not intervene.

In Fig. 5, we fix $\nu = 1.2$ and thus illustrate a case in which an environmental tax alone is not sufficient to improve the situation. As pollution intensity is high, a policy mix can be efficient if the health effect of pollution is not too important while the effect of health expenditure is. We thus consider $\bar{\theta} = 0.8$ and $\underline{\theta} = 0.1$. For policy instruments, we fix $\tau_p = 0.1$ and $\tau_s = 0.05$ but the illustration holds for a large set of combinations.[18,19] As illustrated, the policy mix can prevent the economy to be stuck in a trap in which inequalities constantly widen across generations. While the trap was inevitable without policy and with an environmental policy alone, a policy mix with the same tax burden (15%) enables the economy to converge toward the state without inequality x^E if its initial relative human capital is sufficiently high ($x_0 \in (0.7, 1)$). Thus, the policy mix can be an efficient tool to address the inequality issue as long as disparities are not too wide.

However, even if a policy mix can be efficient for a larger set of emission intensity than an environmental policy alone, it is not necessarily a better option to address inequality. This is represented in Fig. 6. Considering the case illustrated in Fig. 2 (with $\nu = 0.3$, $\bar{\theta} = 0.6$, $\underline{\theta} = 0.4$), both policies can be used to reduce disparities among households. Nevertheless, for a given tax burden, long-term inequalities can be avoided when the policy consists only in reducing pollution ($\tau_p = 0.15$ and $\tau_s = 0$), while it is not the case when it is divided between health and environmental policies ($\tau_p = 0.1$ and $\tau_s = 0.05$ for example).

Therefore, these two policies focusing on the health effects of pollution on children represent interesting tools to address the inequality issue. Both an environmental policy alone and a policy mix composed of environmental and health instruments can reduce inequalities in the economy and enable an economy to escape from the inequality trap in which disparities are persistently widening. However, the efficiency of these policies is also limited, especially by the negative income effect of taxes that dominates when the emission intensity is too high and/or if disparities are too wide. Choosing one or the other depends on the sensitivity of children's health with respect to pollution and parental investment in health, on which further data are needed. When none of these policies are sufficient, a redistributive policy needs to be set as a complementary tool to reduce disparities among households.

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[18] Given these calibrations, the equilibrium subsidy is equal to $\sigma = 0.14$.

[19] Note that to have a policy mix that reduces inequality, this is not necessary to have $\tau_s \geqslant \frac{(\lambda+\alpha\gamma)(\nu-1)}{1+\gamma\beta}$ as this condition is only sufficient.

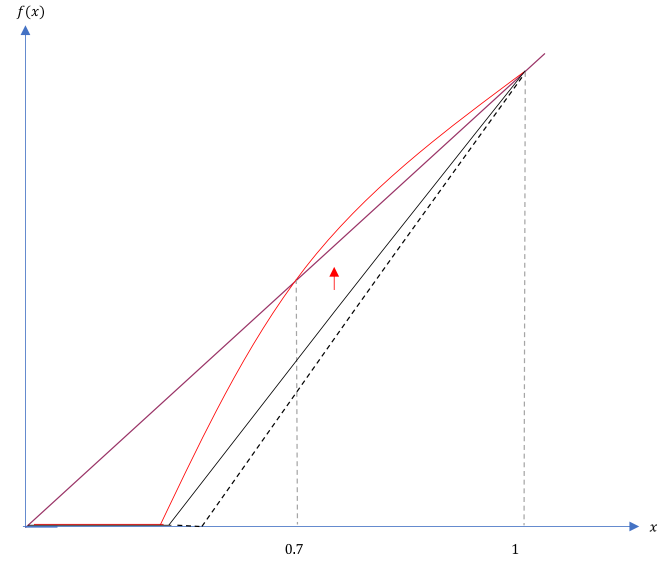

Fig. 5. Effect of the policy mix with $\nu = 1.2$, $\bar{\theta} = 0.8$, $\underline{\theta} = 0.1$. Black solid curve: economy without policy, black dotted curve: economy with pollution tax $\tau_p = 0.15$, red curve: economy with policy mix $\tau_p = 0.1$ and $\tau_s = 0.05$.

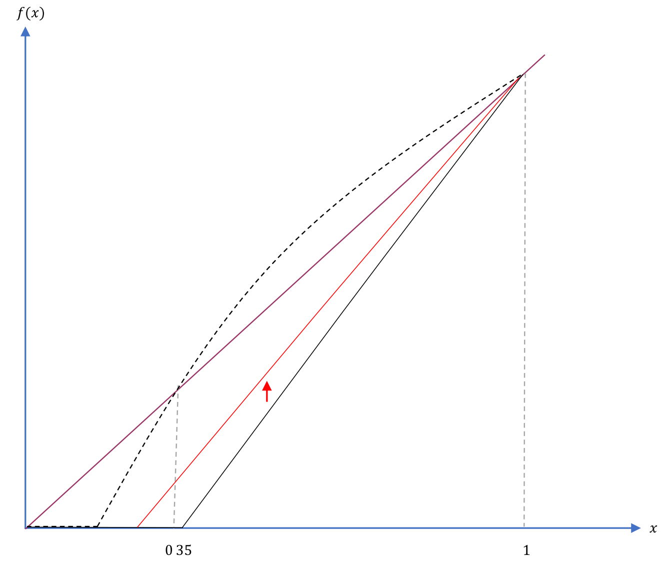

Fig. 6. Effect of the policy mix with $\nu = 0.3$, $\bar{\theta} = 0.6$, $\underline{\theta} = 0.4$. Black solid curve: economy without policy, black dotted curve: economy with pollution tax $\tau_p = 0.15$, red curve: economy with policy mix $\tau_p = 0.1$ and $\tau_s = 0.05$.

6. Concluding remarks

Evidence shows that children are highly vulnerable to the health effects of pollution, that these effects cause both short- and long-term damaging economic consequences and that they are unequally distributed in the population according to the socioeconomic status of parents. However, most prior works abstract from these features to examine the dynamics of inequalities. This paper contributes to the theoretical literature on social mobility and inequality by showing the role of the health effects of pollution during childhood in the intergenerational transmission of inequality and the role that environmental and health policies can play to address this issue.

Considering how children's health may be affected by pollution and by parental expenditure to reduce this detrimental effect, we represent the heterogeneous vulnerability of agents to pollution and how it evolves endogenously across time. In reality, a lot of factors participate in the widening of disparities across time. However, we emphasize that pollution is a key factor explaining human capital divergence among households. Even if we consider a framework in which human capital convergence is usually ensured and if disparities are initially low, we find that the economy always exhibits inequalities in the long run if the emission intensity of production is not small enough. Moreover, through a numerical calibration of the model on developed countries data, we show that in this case the economy is most likely to be stuck in an inequality trap in which disparities are persistently widening across generations. The heterogeneity of agents in terms of human capital entails that parents' abilities to reduce the harmful effects of pollution differ. It follows that children from poor households have more health issues due to pollution and hence more difficulties to acquire human capital than the others, which makes disparities increase across time.

Given these results, we examine if policies focusing on this mechanism can be successfully implemented to reduce the intergenerational transmission of inequality coming from pollution. We show that an environmental policy consisting in taxing the polluting production to fund public abatement can be used to reduce inequality and enable the economy to escape from the trap. Nevertheless, it is not always sufficient and can even be counterproductive, because the negative effect of the improvement in the environment on inequality can be outweighed by the effect of the tax on households' income. This is the case when the emission intensity of production is too high and/or if inequalities are too wide. Finally, we reveal that a policy mix consisting in environmental and health policy tools can be a better solution to reduce inequality, as it is efficient for a larger range of emission intensity if the children's health is sufficiently sensitive to parental health expenditure.

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Appendix

A.1. Proof of Proposition 1

The function $f(x)$ is increasing, with $f(\underline{x}) = 0$ and $f(1) = 1$, thus $x = 1$ is a steady state. Examining the second derivative of the $f(x)$, we see that the function can be concave or convex, meaning that we can observe one or multiple steady states.

We examine the stability properties of the steady state $x = 1$. As we cannot examine precisely the shape of the function $f(x)$, and hence conduct a global stability analysis, we focus on the local stability. We have

$$
\begin{aligned}
f'(x) = {} & x^{\mu-1}\left[\frac{\bar{\theta}x_t - \underline{\theta}\nu(\xi x_t + (1-\xi))}{\bar{\theta} - \underline{\theta}\nu(\xi x_t + (1-\xi))}\right]^{\alpha+\beta} \\
& \times \left[\mu + \frac{x(\alpha+\beta)}{\bar{\theta} - \underline{\theta}\nu(\xi x_t + (1-\xi))}\frac{\bar{\theta}(\bar{\theta} - \underline{\theta}\nu)}{\bar{\theta}x_t - \underline{\theta}\nu(\xi x_t + (1-\xi))}\right]
\end{aligned}
$$

with

$$
f'(1) = \mu + \frac{(\alpha+\beta)\bar{\theta}}{\bar{\theta} - \underline{\theta}\nu}.
$$

From this expression, we can define a critical threshold on ν, $\hat{\nu} = \frac{\bar{\theta}(1-\alpha-\beta-\mu)}{\underline{\theta}(1-\mu)}$, to characterize the local stability properties of $x = 1$.

Note that in case of stability, $f(1)$ cuts the bisector by the top. This means that $f(x)$ cuts the bisector at least one time from the bottom between $\underline{x}$ and 1: there is necessarily (at least) another steady state that is with inequality and unstable. Hence, stability condition for $x = 1$ is a sufficient condition to have multiple steady states (as long as $\nu > 0$). □

A.2. Proof of Proposition 2

Using Definition 1, a steady state satisfies

$$\begin{aligned} g(x) &\equiv x^{1-\mu}\left(\bar{\theta} - \underline{\theta}\nu(\xi x_t + (1-\xi))\right)^{\alpha+\beta} \\ &= \left(\bar{\theta}x_t - \underline{\theta}\nu(\xi x_t + (1-\xi))\right)^{\alpha+\beta} \equiv z(x) \end{aligned}$$

with

- $z(x)$ increasing and concave, with $z(\underline{x}) = 0$
- $g(x) > 0$ for all $x \geqslant \underline{x}$. Moreover, $g(x)$ is increasing and then decreasing, and achieves its maximal value for $\tilde{x} = \frac{(1-\mu)(\bar{\theta}-\underline{\theta}\nu(1-\xi))}{\underline{\theta}\nu\xi(1-\mu+\alpha+\beta)}$ $(g'(\tilde{x}) = 0)$.
- $g(1) = z(1)$.

From these properties, we deduce that if $\underline{x} > \tilde{x}$, $g(x)$ is always decreasing on the interval $x \in [\underline{x}, 1]$, meaning that it crosses $z(x)$ only once, at $x = 1$. Thus, the condition $\underline{x} > \tilde{x}$ is sufficient to have a unique steady state $x = 1$. We have

$$\underline{x} > \tilde{x} \quad \Rightarrow (1-\mu)\bar{\theta}(\bar{\theta} - \underline{\theta}\nu) < (1-\xi)\xi(\alpha+\beta)(\underline{\theta}\nu)^2.$$

Note that several steady states are required to have $x = 1$ stable. A necessary (but not sufficient) condition to converge toward a long-term state without inequality is thus to have $\underline{x} < \tilde{x}$. Otherwise, there is only one steady state which is necessarily unstable in our model: the economy cannot converge to a situation in which $x = 1$ and there are inequalities. □

A.3. Proof of Proposition 3

We examine in this Appendix sufficient conditions to have multiple steady states and $x = 1$ unstable.

This requires to have $\nu > \hat{\nu}$ ($x = 1$ unstable) and that there exists at least a $x \in (\underline{x}, 1)$ satisfying $f(x) > x$. This last condition implies

$$x^{\frac{1-\mu}{\alpha+\beta}} < \frac{\bar{\theta}x - \underline{\theta}\nu(\xi x + (1-\xi))}{\bar{\theta} - \underline{\theta}\nu(\xi x + (1-\xi))}$$

and can be written as

$$\frac{1-\mu}{\alpha+\beta} > \frac{\ln\left[\bar{\theta}x - \underline{\theta}\nu(\xi x + (1-\xi))\right] - \ln\left[\bar{\theta} - \underline{\theta}\nu(\xi x + (1-\xi))\right]}{\ln x}.$$

For $x = 1/2$, this inequality (i.e $f(1/2) > 1/2$) becomes

$$\frac{1-\mu}{\alpha+\beta} > \frac{\ln\left[\bar{\theta}/2 - \underline{\theta}\nu(1-0.5\xi)\right] - \ln\left[\bar{\theta} - \underline{\theta}\nu(1-0.5\xi)\right]}{\ln(1/2)}$$

$$\frac{1-\mu}{\alpha+\beta} > \frac{\ln\left[\bar{\theta} - 2\underline{\theta}\nu(1-0.5\xi)\right] - \ln\left[\bar{\theta} - \underline{\theta}\nu(1-0.5\xi)\right] - \ln 2}{-\ln 2}$$

$$\frac{1-\mu}{\alpha+\beta} > 1 + \frac{\ln\left[\bar{\theta} - \underline{\theta}\nu(1-0.5\xi)\right] - \ln\left[\bar{\theta} - 2\underline{\theta}\nu(1-0.5\xi)\right]}{\ln 2}. \tag{28}$$

The term on the right hand side is increasing in ν and equal to one for $\nu = 0$. Under Assumption 1, this means that there exists a $\tilde{\nu}$ such that this inequality holds for $\nu < \tilde{\nu}$ and does not hold for $\nu > \tilde{\nu}$.

As we focus on the cases in which $\nu > \hat{\nu}$, the previous inequality can be observed in our context only if $\hat{\nu} < \tilde{\nu}$. Thus, inequality (28) has to be possible when $\nu = \hat{\nu}$. This implies

$$\begin{aligned} &\frac{1-\mu}{\alpha+\beta} + \frac{\ln\left[1-\mu-2(1-\alpha-\beta-\mu)(1-0.5\xi)\right]}{\ln 2} \\ &> 1 + \frac{\ln\left[1-\mu-(1-\alpha-\beta-\mu)(1-0.5\xi)\right]}{\ln 2} \end{aligned}$$

There exists a set of parameters satisfying this inequality, i.e. when ξ, and/or $\mu+\beta+\alpha$ sufficiently close to one. In that case, there exists a $\tilde{\nu}$ such that when $\hat{\nu} < \nu < \tilde{\nu}$, the economy is characterized by x^E unstable and at least another steady state $x < 1/2$ which is stable. □

A.4. The model with the policy instruments

With the policy instruments introduced in Section 5, pollution and the budget constraint of an adult become (18) and (19). Therefore, the following first order conditions of an adult become

$$e_t^i = \frac{\gamma\beta}{\bar{\theta}(1+\gamma\beta+\gamma\alpha+\lambda)}\left[\bar{\theta}h_t^i w_t - (1-\sigma_t)\underline{\theta}P_t\right] \tag{29}$$

and

$$s_t^i = \frac{(\lambda+\alpha\gamma)\bar{\theta}h_t^i w_t + (1-\sigma_t)\underline{\theta}(1+\gamma\beta)P_t}{(1-\sigma_t)\bar{\theta}(1+\gamma\beta+\gamma\alpha+\lambda)}. \tag{30}$$

The firm maximizes its profit $(1-\tau_p-\tau_s)Y_t - w_t\bar{h}_t$, such that

$$w_t = A(1-\tau_p-\tau_s). \tag{31}$$

The human capital accumulation of the two types of agents can be rewritten as

$$\begin{aligned} h_{t+1}^s = \epsilon C_1 &\frac{\left((1-\tau_p-\tau_s)\bar{\theta}h_t^s - \underline{\theta}(1-\sigma_t)(\nu-\tau_p)(\xi h_t^u + (1-\xi)h_t^s)\right)^{\alpha+\beta}}{\left(1+(\nu-\tau_p)A(\xi h_t^u + (1-\xi)h_t^s)\right)^{\alpha}(1-\sigma_t)^{\alpha}} \\ &\times \left(h_t^s\right)^{\mu}(\xi h_t^u + (1-\xi)h_t^s)^{\delta} \end{aligned} \tag{32}$$

and

$$\begin{aligned} h_{t+1}^u = \epsilon C_1 &\frac{\left((1-\tau_p-\tau_s)\bar{\theta}h_t^u - \underline{\theta}(1-\sigma_t)(\nu-\tau_p)(\xi h_t^u + (1-\xi)h_t^s)\right)^{\alpha+\beta}}{\left(1+(\nu-\tau_p)A(\xi h_t^u + (1-\xi)h_t^s)\right)^{\alpha}(1-\sigma_t)^{\alpha}} \\ &\times \left(h_t^u\right)^{\mu}(\xi h_t^u + (1-\xi)h_t^s)^{\delta} \end{aligned} \tag{33}$$

with

$$C_1 \equiv \frac{(\lambda+\alpha\gamma)^{\alpha}}{(1+\gamma\beta+\gamma\alpha+\lambda)^{\alpha+\beta}}\left(\frac{\gamma\beta}{\bar{\theta}}\right)^{\beta}A^{\alpha+\beta}.$$

From the government budget constraint, we have

$$\begin{aligned} &\sigma_t\sum_{i=u,s}\frac{(\lambda+\alpha\gamma)\bar{\theta}\xi^i h_t^i(1-\tau_p-\tau_s) + (1-\sigma_t)\underline{\theta}(1+\gamma\beta)(\nu-\tau_p)(\xi h_t^u + (1-\xi)h_t^s)}{(1-\sigma_t)\bar{\theta}(1+\gamma\beta+\gamma\alpha+\lambda)} \\ &= \tau_s(\xi h_t^u + (1-\xi)h_t^s) \end{aligned}$$

that can be rewritten as

$$\begin{aligned} &\sigma_t(\lambda+\alpha\gamma)\bar{\theta}(\xi h_t^u + (1-\xi)h_t^s)(1-\tau_p-\tau_s) = (1-\sigma_t) \\ &\quad\times(\xi h_t^u + (1-\xi)h_t^s)\left[\tau_s\bar{\theta}(1+\gamma\beta+\gamma\alpha+\lambda) - \sigma_t\underline{\theta}(1+\gamma\beta)(\nu-\tau_p)\right]. \end{aligned}$$

After simplifications, we see that the equilibrium value of σ is time independent and satisfies the following equality:

$$\begin{aligned} \sigma(\lambda+\alpha\gamma)\bar{\theta}(1-\tau_p-\tau_s) = (1-\sigma)&\left[\tau_s\bar{\theta}(1+\gamma\beta+\gamma\alpha+\lambda)\right. \\ &\left.-\sigma\underline{\theta}(1+\gamma\beta)(\nu-\tau_p)\right]. \end{aligned} \tag{34}$$

From this equality, we have a unique equilibrium value for σ that depends on taxes. It increases with both τ_p and τ_s. It is equal to 0 when $\tau_s = 0$ and tends to 1 when τ_s tends to 1 as well. □

A.5. Proof of Proposition 5

The combined effects of both instruments depend on the response of subsidy rate σ to tax variation, i.e on the values of $\partial\sigma/\partial\tau_p$ and $\partial\sigma/\partial\tau_s$. The equilibrium value for σ satisfies the equality (34). This equality can be written as

$$\sigma(\lambda+\alpha\gamma)(1-\tau_p-\tau_s) = (1-\sigma)\left[\tau_s(1+\gamma\beta+\gamma\alpha+\lambda)\right.$$
$$\left. -\sigma\frac{\underline{\theta}}{\bar{\theta}}(1+\gamma\beta)(\nu-\tau_p)\right].$$

The equilibrium value for σ increases with $\frac{\bar{\theta}}{\underline{\theta}}$. Moreover, we have that $\lim_{\bar{\theta}/\underline{\theta}\to 0}\sigma = 0$ and $\lim_{\bar{\theta}/\underline{\theta}\to\infty}\sigma = \frac{\tau_s(1+\gamma\beta+\gamma\alpha+\lambda)}{\tau_s(1+\gamma\beta+\gamma\alpha+\lambda)+(\lambda+\alpha\gamma)(1-\tau_p-\tau_s)}$.

We pay a particular attention to the effect of the policy mix in the extreme case in which $\frac{\bar{\theta}}{\underline{\theta}}$ is infinitely high. For that case, we have

$$\partial\sigma/\partial\tau_p = \frac{\tau_s(1+\gamma\beta+\gamma\alpha+\lambda)(\lambda+\alpha\gamma)}{(\tau_s(1+\gamma\beta+\gamma\alpha+\lambda)+\lambda(1-\tau_p-\tau_s))^2}$$

$$\partial\sigma/\partial\tau_s = \frac{(1-\tau_p)(1+\gamma\beta+\gamma\alpha+\lambda)(\lambda+\alpha\gamma)}{(\tau_s(1+\gamma\beta+\gamma\alpha+\lambda)+\lambda(1-\tau_p-\tau_s))^2}$$

and, from Lemma 1,

$$Sign\ \ \mathrm{d}f(x_t) = (1-x_t)\left[Sign\frac{\partial f(x_t)}{\partial\tau_p}\mathrm{d}\tau_p + (\nu-\tau_p)Sign\frac{\partial f(x_t)}{\partial\tau_s}\mathrm{d}\tau_s\right]$$

with

$$Sign\frac{\partial f(x_t)}{\partial\tau_s} = \frac{(1+\gamma\beta)(\lambda+\alpha\gamma)(1-\tau_p-\tau_s)^2}{(\tau_s(1+\gamma\beta+\gamma\alpha+\lambda)+(\lambda+\alpha\gamma)(1-\tau_p-\tau_s))^2} > 0$$

and

$$Sign\frac{\partial f(x_t)}{\partial\tau_p} = \frac{(\tau_s(1+\gamma\beta)+(\lambda+\alpha\gamma)(1-\nu))(\lambda+\alpha\gamma)(1-\tau_p-\tau_s)^2}{(\tau_s(1+\gamma\beta+\gamma\alpha+\lambda)+(\lambda+\alpha\gamma)(1-\tau_p-\tau_s))^2}.$$

We have $\frac{\partial f(x_t)}{\partial\tau_p} \geqslant 0$ (resp. < 0) for $\tau_s \geqslant \frac{(\lambda+\alpha\gamma)(\nu-1)}{1+\gamma\beta}$ (resp. $\tau_s < \frac{(\lambda+\alpha\gamma)(\nu-1)}{1+\gamma\beta}$). This means that when

$$\nu < 1 + \frac{1+\gamma\beta}{\lambda+\alpha\gamma}$$

there always exists a value for $\tau_s < 1$ ensuring $\frac{\partial f(x_t)}{\partial\tau_p} > 0$. As we have $\frac{\partial f(x_t)}{\partial\tau_s} > 0$ for all possible taxes satisfying Assumption 2 and $\tau_p+\tau_s < 1$, the condition $\nu < 1+\frac{1+\gamma\beta}{\lambda+\alpha\gamma}$ associated with $\frac{\bar{\theta}}{\underline{\theta}}$ high enough is sufficient to have $\mathrm{d}f(x_t) > 0$ when both instruments are used. □

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ORIGINAL ARTICLE

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Environment, public debt, and epidemics

Marion Davin[1] | Mouez Fodha[2] | Thomas Seegmuller[3]

[1]Center for Environmental Economics of Montpellier, University of Montpellier, CNRS, INRAE, SupAgro, Montpellier, France

[2]University Paris 1 Panthéon-Sorbonne and Paris School of Economics, Paris, France

[3]Aix Marseille School of Economics, Aix Marseille University, CNRS, Marseille, France

Correspondence
Marion Davin, Center for Environmental Economics of Montpellier, University of Montpellier, CNRS, INRAE, SupAgro, Montpellier, France.
Email: marion.davin@umontpellier.fr

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Abstract
We study whether fiscal policies, especially public debt, can help to curb the macroeconomic and health consequences of epidemics. Our approach is based on three main features: we introduce the dynamics of epidemics in an overlapping generations model to take into account that old people are more vulnerable; people are more easily infected when pollution is high; public spending in health care and public debt can be used to tackle the effects of epidemics. We show that fiscal policies can promote convergence to a stable disease-free steady state. When public policies are not able to permanently eradicate the epidemic, public debt, and income transfers could reduce the number of infected people and increase capital and GDP per capita. As a prerequisite, pollution intensity should not be too high. Finally, we define a household subsidy policy that eliminates income and welfare inequalities between healthy and infected individuals.

1 | INTRODUCTION

The recent Covid-19 epidemic is one of the most serious threats to health in the last decades. It has revealed how managing a pandemic to limit health and economic costs is challenging. In a context in which environmental factors have been found to influence the transmissions of viral pathogens and the disease emergence, there is a need to well understand the interplay between the health and economic impacts of epidemics. This is the aim of this paper.

Without restricting our attention to a particular epidemic, we analyze the effects of public interventions to control the disease, in particular health public spending and fiscal policy with public debt. We consider fiscal policy and public debt in the discussion as the management of sanitary crisis usually goes along with extraordinary public measures. The OECD points out the sharp increase in public debt expected in the OECD area because of the Covid-19 crisis.[1] For other diseases like HIV or malaria, debt relief is frequently mentioned as an instrument to help endemic countries to control epidemics (Abah, 2020; Snow et al., 2010). This illustrates that debt management is expected to play a crucial role to try to control or eradicate this type of disease.

Another important aspect to consider when examining the interplay between epidemics and economics is the environmental issue. Growing evidence suggests that environmental factors has an effect on the rate of spread of epidemics. Air pollution, such as CO2 and PM, is a factor in accelerating virus transmission between humans. Pollution particles behave as vehicles for virus transport, especially in epidemics where the mode of transmission is mainly via aerosols (Bourdrel et al., 2021; Domingo & Rovira, 2020; Rohrer et al., 2020). Moreover, there is an indirect effect of pollution on the rate of propagation, through the consequences of pollution on the health of individuals, particularly the most fragile. Pollution makes individuals more vulnerable and therefore less resistant because they are more immunocompromised.

In line with Augier and Yaly (2013), Chakraborty et al. (2010, 2014), Momota et al. (2005), we develop an overlapping generations (OLG) model with epidemics, that we enriched with an environmental dimension and the introduction of a government. This model offers the interest to consider heterogeneity of agents according to their age and is relevant to analyze the role of public debt. There are three-period lived households with young inactive agents, working adults, and old retirees. The dynamics of epidemics are formalized by introducing a susceptible-infected-susceptible (SIS) model, as in Bosi and Desmarchelier (2020), Goenka and Liu (2012, 2020), or Goenka et al. (2014).

In our model, we first consider that the impacts of the epidemic depend on the age of the person affected: the older agent bears a premature risk of death while the adult agent will be sick, without fatal consequences, but will have to take time off work. Indeed, empirical studies show that the mortality of elderly patients is higher than that of young and middle-aged patients during epidemics, because of their higher vulnerability. Taking the recent example of Covid-19, elderly patients are more likely to progress to severe disease (see Liu et al., 2020; Williamson et al., 2020) and hence, they are more affected by saturated health's system capacities entailed by the epidemics. Second, in line with the arguments previously mentioned, we consider that degradation of the environmental quality increases the rate of contagion of the epidemic. Finally, health policy consisting in public spending to prevent, detect, control, and treat quickly the epidemics, contributes to push down the contagion rate. The government finances its expenditures through taxation of income and production, but also through the issuance of public debt. In line with Geoffard and Philipson (1997),[2] we assume that health policy reduces the transmission of the virus but does not allow to have full immunity.

The stable steady state is indeed characterized by the presence of the virus. However, the government can increase health expenditures to slow down the spread of the virus. Such a strategy can allow to rule out the endemic steady state and converge to a disease-free steady

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[1] According to OECD (2020b), "For the OECD area as a whole, outstanding central government debt is expected to increase from USD 47 trillion in 2019 to USD 52.7 trillion at the end of 2020. This is USD 3.5 trillion higher than the pre-Covid estimate. As a result of both the rapid increase in borrowing needs and the decline in GDP across OECD economies, the central government marketable debt-to-GDP ratio for the OECD area is projected to increase by 13.4 percentage points to around 86% in 2020, the largest increase in a single year since 2007."

[2] Even if public funds are directed towards the development of a vaccine, Geoffard and Philipson (1997) underline the difficulties for policies to increase demand for vaccine and hence to achieve eradication with vaccine.

state. These results are conditioned by the pollution intensity of production: the higher the pollution intensity, the more difficult it is to fight the epidemic. If the public policy is not able to remove entirely the epidemic, the economy converges towards an endemic steady state. It could, however, be used to reduce the number of infected people and increase capital per capita in the long run endemic equilibrium. The complexity of the interactions between fiscal policy and the fight against epidemics is highlighted. In fact, on the one hand, any increase in public debt leads to a crowding-out effect on productive capital. The latter implies a drop in production, wages, savings, and tax revenues, which curbs the expected effects of increased public spending, and reduces the effectiveness of public policy. At the same time, it also slows down pollution and plays a positive role in the fight against the virus. On the other hand, the increase in debt allows an increase in public spending, and thus a slowing of the epidemic, which has a stimulus effect on the economy through the increase in the number of workers, savings, and capital (crowding-in effect). The final outcome depends on the relative magnitude of these two channels. We show that the crowding-in effect dominates if the rate of pollution emission is not too high.

At the endemic steady state, there are income inequalities between infected and healthy people. We show that it is possible to design an appropriate redistribution income policy to address welfare disparities. This policy consists of a differentiated transfer of income for workers and the sick. It complements the public policy to combat the virus. We emphasize that such intervention can be costly for healthy people when public budget for transfers is not sufficiently important.

Our results underline the importance to maintain a high level of public health spending and a high public budget for transfer to control an epidemic and address its economic consequences. This implies a sufficient level of public debt. Our conclusions are thus in line with the proposal of Douglas and Raudla (2020) for the US economy, who argue that the States should suspend their balanced budget rules and norms, and run deficits in their operating budgets to maintain services and meet additional obligations due to the pandemic of Covid-19.

Our paper relates to the large literature interested in the analysis of the interactions between economics and epidemics. On the one hand, there is important literature characterized by age specific effect of epidemics (Boucekkine et al., 2009; Boucekkine & Laffargue, 2010; Fabbri et al., 2021[3]). On the other hand, some models are based on mathematical frameworks developed by epidemiologists (see Hethcote, 2000, for an interesting survey); they expanded with the HIV epidemic (see e.g., Geoffard & Philipson, 1997). This literature has obviously been revived and adapted to the specificities of the Covid-19 (see e.g., Acemoglu et al., 2021; Alvarez et al., 2021; Goenka et al., 2021; Gori et al., 2021; Hritonenko et al., 2021). Nonetheless, no study considers simultaneously the differentiated effects of the consequences of the virus according to the age of the infected persons, and the role played by the environment in the spread and incidence of the virus. Moreover, public actions examined in the literature dealing with epidemics and economics, such as confinement, social distancing and the speed at which a vaccine develops, greatly differ from those explored in this paper.

We highlight in this study the direct consequences of public finance on epidemics and vice-versa. We show that in the absence of full immunity, health care spending can play a major role in the fight against the epidemic and public debt can push up GDP per capita. Our paper thus complements the literature taking into account the costs and benefits of public policies and the

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[3] This last paper is based on M'Kendrick (1925) setting.

specific impacts of the epidemic by age groups. In this way, we provide new intuitions about the effects of public debt and pollution on economic aggregates and epidemics propagation.

The rest of this paper is organized as follows. Section 2 presents the model with epidemics. Section 3 defines the intertemporal equilibrium. Section 4 analyzes the existence of steady states and Section 5 the convergence to the steady states. Section 6 focuses on the role of fiscal policy. Section 7 presents transfer schemes to address inequalities among agents. Finally, Section 8 concludes, while technical details are relegated to an Appendix.

2 | AN OLG MODEL WITH POLLUTION AND EPIDEMICS

We consider a discrete-time ($t = 0, 1, \ldots$) OLG model. The dynamics of epidemics follow an SIS model. There are three types of agents, households, a government, and firms which generate pollution.

2.1 | Environmental quality

Environmental quality decreases with pollution P_t, which is a flow that proportionally raises with production Y_t:

$$P_t = \alpha Y_t,$$

where $\alpha > 0$ is the pollution rate.

This global pollution index encompasses the degradation imposed by human activity on the quality of the environment. It reflects both the level of pollutant emissions and changes in biodiversity. It can be represented by Ecological Footprint measurements or by Environmental Performance Index (Wendling et al., 2020).

2.2 | Population and epidemics

As in Bosi and Desmarchelier (2020), Goenka and Liu (2012, 2020), or Goenka et al. (2014), the dynamics of epidemics are driven by a SIS model, with susceptible and infected people. It differs from the Susceptible-Infectious-Recovered (SIR) model recently used in economics (see e.g., Acemoglu et al., 2021; Eichenbaum et al., 2020) which also introduced the category of recovered people.[4]

We consider a model with three period-lived agents: childhood, adulthood, and old age. The population size of a generation is constant and equal to N. When young, an agent has contact with other generations what makes her susceptible or infected at the beginning of her adult life. Thus, at the beginning of each period, there are also N adults and N old consumers, which inherit their type from the previous period. Let H_t^i be healthy susceptible people and I_t^i be infected people, with the superscript $i = a$ for adult people and $i = o$ for old people. At time t, we have $2N = H_t^a + H_t^o + I_t^a + I_t^o$. We assume that susceptibility to infection does not depend

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[4] In our OLG framework, considering the SIS rather than the SIR model does not alter the results.

on age. The number of adult and old agents being susceptible and infected are thus the same, that is, $H_t^a = H_t^o = H_t$ and $I_t^a = I_t^o = I_t$.

Nevertheless, the health impacts of the infection are assumed to be heterogeneous, that is, age-dependent.[5] This is consistent with the fact that older infected people really face a more important probability to die and to develop severe illness, because of physiological changes that make them more vulnerable. While the size of adult population is not affected by the proportion of infected people, epidemics shorten the probability to enter old age. The more infected old people there are in the population, the higher the probability to die prematurely. We do not consider the individual effect of infection on mortality, but we rather focus on the negative externality associated with epidemics for all elderly population. The general intuition is that a high number of infected people in the economy tends to reduce the efficiency of medical services or can be a source of congestion effects in the healthcare sector, and hence entails a negative externality on the old vulnerable population. Several studies have underlined the negative indirect effects associated with important epidemics as they tend to disrupt and suspend health services (Chang et al., 2004; Kontis et al., 2020; Rust et al., 2009). As an example, this is also typically what we observe since the beginning of the Covid-19 crisis. Elderly patients are more likely to progress to severe disease (Liu et al., 2020; Williamson et al., 2020) and thus, they are more affected by saturated health's system capacities.

At the beginning of the period, we have $2N = 2H_t + 2I_t$ of adult and old people, which is equivalent to $1 = h_t + i_t$, where $h_t = H_t/N$ represents the share of healthy people and $i_t = I_t/N$ represents the share of infected people. Note that i_t can also be interpreted as the likelihood of being infected.

Let $\theta_t > 0$ be the transmission rate of the epidemics among healthy agents and $\gamma \in (0, 1)$ the rate of recovery among infected people. The rate θ_t can also be interpreted as the average number of contacts per unit time such that an infective transmits the disease. The dynamics of healthy people are given by:

$$H_{t+1} = H_t + \gamma I_t - \theta \frac{I_t}{N} H_t,$$

where γI_t represents cured people and $\theta_t \frac{I_t}{N} H_t$ new people infected, which is given by healthy people (H_t) times the risk of meeting infected individual $(\frac{I_t}{N})$ times the transmission rate (θ_t).

The dynamics of infected people are exactly the opposite:[6]

$$I_{t+1} = I_t - \gamma I_t + \theta_t \frac{I_t}{N} H_t.$$

These last two equations rewrite:

$$h_{t+1} = \gamma i_t + (1 - \theta_t i_t) h_t, \tag{1}$$

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[5] We consider an OLG model precisely to take into account that adult and old people do not face the same consequences of being infected.

[6] Note that we assume that the proportion of people which die prematurely during old age is too negligible in the society to affect the dynamics of epidemics.

$$i_{t+1} = (1-\gamma)i_t + \theta_t i_t h_t. \qquad (2)$$

On the one hand, to keep things as simple as possible, the rate of recovery γ is constant, as in Goenka and Liu (2020). On the other hand, we assume that the transmission rate θ_t is increasing with pollution P_t. Many evidence support that air pollution raises the transmission of respiratory viral infections (see Domingo & Rovira, 2020, for a survey). The recent Covid crisis confirm the relevance of the assumption. For example, Cole et al. (2020) highlight that $PM_{2.5}$ and NO_2 concentrations have a positive link with Covid-19 cases, hospital admissions.

Climate variability has also lead to a proliferation of vector-borne diseases, like malaria, resulting in an increase in transmission (Barreca & Shimshack, 2012; Rohr & Cohen, 2020). The transmission rate θ_t is also decreasing with public expenditures in health care G_t. The higher G_t, the higher public health response capacity and the lower the spread of epidemics. We assume that health policy does not allow to build full immunity, in line with the arguments of Geoffard and Philipson (1997). According to them, even when vaccines are available, it is difficult for policies to increase demand for it and hence to achieve eradication. Moreover, many viruses, such as malaria or HIV, have not found a cure and policies to control the spread are limited to subsidies and protective spending. As a result, G_t could be masks, tests, emergency services, controls, information campaign, or vaccine among the others.

Let $g_t \equiv G_t/N$ be public expenditures per adult and $p_t \equiv P_t/N$ pollution per adult. For tractability, we assume:

Assumption 1. $\theta_t = \theta(G_t/P_t) = \theta(g_t/p_t) > 0$ for all g_t/p_t, with $\theta'(g_t/p_t) < 0$. In addition, $\theta_t i_t < 1$.

The inequality $\theta_t i_t < 1$ means that the probability for healthy people to be infected is less than one. Using (1), it also implies that $h_t > 0$ whatever the value of γ.

2.3 | Households

The economy is populated by OLG of agents living for three periods. As we aim at analyzing the role of public policies, the non-Ricardian properties of the OLG model are convenient. Finally, it is a tractable way to consider the coexistence of heterogeneous agents at each period of time. We will have adult savers which will live at the same time that elderly who spend their remunerated savings. Considering such an OLG model where the dynamics of infected are driven by an SIS model means that the length of a period is quite long with respect to the period of being infected for many diseases. Nonetheless, some papers already consider infectious disease and overlapping generations model. For example, in the OLG models considered by Augier and Yaly (2013), Chakraborty et al. (2010, 2014), Momota et al. (2005), the dynamics of epidemics is also driven by a stock variable. Their results highlight interesting mechanisms, confirming that this framework remains well adapted for the study of population-epidemic dynamics interactions. As it is well-known, more complicated frameworks could rationalize heterogeneous behaviors between workers and retirees, for instance models with infinitely lived agents facing some financial constraints.[7] We could also note that the behavior of agents

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[7] See for instance Woodford (1986) and Kocherlakota (1992).

will be summarized by their saving behavior which is closely related to what we get in a standard Solow model.

When young, an agent does neither consume nor work but, as we already mentioned, has contact with other generations such that she becomes susceptible or infected at the next period. In contrast, an agent is active and consume at the adult age, and is retired and consumes at the old age. The preferences of the household $j \in \{1, ..., N\}$ born at period $t-1$ are represented by the following utility function over consumption when adult c_{jt} and old d_{jt+1}:

$$\ln c_{jt} + \beta(h_{t+1}) \ln d_{jt+1}, \tag{3}$$

where $\beta(h_{t+1}) \in (0, 1]$ measures the survival probability. It means that either the adult survives at the old age or he dies at the beginning of the old age. This utility function means that, whereas an infected adult has no chance to die at the adult age, the probability to die at the beginning of the old age increases with the proportion of infected people among old agents or equivalently the survival probability increases with the proportion of noninfected susceptible people h_{t+1} at old age, that is, $\beta'(h_{t+1}) > 0$. We also assume that $\beta(h_{t+1})$ is strictly concave, which implies that $\beta'(h_{t+1}) < \beta'(0)$. This specification is similar to Momota et al. (2005), that considers the negative effect of the prevalence of the disease on the probability to be alive in the second period of life. The sensitivity of β to h can also be interpreted as the limited resilience of healthcare institutes. The possible saturation of the health system when the proportion of infected becomes high leads to a decrease of the survival probability of the elderly population.

The budget constraints faced by an individual $j \in \{1, ..., N\}$ are given by:

$$\sigma_{jt} + c_{jt} = \Omega_{jt} + \tau_{jt}, \tag{4}$$

$$d_{jt+1} = \frac{r_{t+1}}{\beta(h_{t+1})} \sigma_{jt}, \tag{5}$$

where σ_{jt} represents savings of individual j. Since each household supplies one unit of labor if she is healthy, Ω_{jt} is the labor income, which is equal to the real wage paid by the firm to workers w_t if individual j is healthy and 0 if she is infected. This means that at periods of epidemics, a share of adults will not work. We note that this is not specific to our framework since it also occurs in OLG models with some labor market imperfections and unemployment (Coimbra et al., 2005; Kaas & von Thadden, 2004; Ono, 2007). Moreover, this is not crucial for our results. What is important is that, at the equilibrium, the income used for aggregate savings will increase with the number of healthy people.

$\tau_{jt} \gtreqless 0$ is a lump-sum subsidy/tax which is specific to each individual and can be used by the government to (partially) cover the loss of labor income. We, therefore, have in mind that for infected people who will not work, τ_{jt} can be interpreted as health insurance or a paid sick leave. As it is empirically established, paid sick leave is implemented by governments in a large number of countries (Scheil-Adlung & Sandner, 2010). Replacement rates vary up to 100% of wages. There is also evidence that paid sick leave has been used as a policy response to protect income through the Covid-19 crisis (OECD, 2020a). Indeed, data suggest that paid sick leave has grown significantly in most countries in the outbreak of the pandemic.

The return of savings is $r_{t+1}/\beta(h_{t+1})$, with r_{t+1} the marginal productivity of capital, because there is perfect annuity on the asset markets.[8]

We deduce that the consumptions and savings of individual j are equal to:

$$c_{jt} = \frac{1}{1 + \beta(h_{t+1})}(\Omega_{jt} + \tau_{jt}), \tag{6}$$

$$d_{jt+1} = \frac{r_{t+1}}{1 + \beta(h_{t+1})}(\Omega_{jt} + \tau_{jt}), \tag{7}$$

$$\sigma_{jt} = \frac{\beta(h_{t+1})}{1 + \beta(h_{t+1})}(\Omega_{jt} + \tau_{jt}). \tag{8}$$

In our model, pollution affects the consequences of the epidemic through two channels, a direct and an indirect one. On the one hand, the direct effect is measured by the effect of pollution on the transmission rate $\theta(g/p)$. The higher the pollution, the higher the rate of spread, and the higher the number of infected individuals. On the other hand, it mechanically lowers the number of healthy individuals h, which reduces the life expectancy of the oldest people $\beta(h)$ and the saving rate $\beta(h)/(1 + \beta(h))$.

2.4 | Firms

Markets are perfectly competitive and production is performed by a representative firm. Output Y_t is produced with labor L_t and capital K_t according to constant returns to scale technology.

$$Y_t = A(h_t)F(K_t, L_t).$$

The total factor productivity $A(h_t)$ experiences a large decrease if the proportion of infected people becomes higher than a threshold:

$$\begin{cases} A(h_t) = 1, & \text{if } h_t > \underline{h}, \\ A(h_t) = A < 1, & \text{otherwise.} \end{cases}$$

$A(h_t)$ acts as an externality in production and the parameter $\underline{h} \in (0, 1)$ is a threshold for epidemics which plays a crucial role on this externality. If the proportion of infected people is positive but sufficiently low ($h_t > \underline{h}$), nothing happens on the productivity. On the contrary, if the proportion of infected people is too high ($h_t \leqslant \underline{h}$), the number of working people is too low to maintain efficient labor, because of costly work disorganization for instance. Moreover, this too low working people can create an inefficient utilization of capital (some units should close or some machines are no more used because not enough people are working). These different arguments allow us to think that the total factor productivity becomes lower when prevalence of disease is sufficiently high. This is in line with Cole and Neumayer (2006) that find a negative impact of poor health, that is, health problems associated to great burden, on total factor productivity.

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[8] For simplification, we also assume complete depreciation of capital.

For tractability, we use a Cobb–Douglas technology:

$$Y_t = A(h_t)L_t f(a_t) = A(h_t)L_t a_t^s$$

with $s \in (0, 1/2)$ the capital share in total income and $a_t = K_t/L_t$ the capital-labor ratio.

Production, at the origin of pollution flow, is taxed by the government at a rate $\tau_t^f \geq 0$. Hence, firms choose inputs by maximizing its profit $(1 - \tau_t^f)Y_t - r_t K_t - w_t L_t$, such that we get:

$$r_t = \left(1 - \tau_t^f\right)A(h_t)sa_t^{s-1} \equiv r(a_t), \tag{9}$$

$$w_t = \left(1 - \tau_t^f\right)A(h_t)(1 - s)a_t^s \equiv w(a_t). \tag{10}$$

2.5 | Public sector

To limit the adverse economic effects of an epidemic, public authorities generally implement a policy mix aiming at improving the health situation and mitigating the effects on the economic activity. In this perspective, we consider that the government can fight the disease and improve health by financing public health expenditures G_t. These spendings have a direct effect on epidemics, since they reduce the rate of transmission θ_t, without allowing to have full immunity. In addition, the government can also limit the economic costs of epidemics by paying some lump-sum subsidies τ_{jt} to adult households. We define $\tau_t = \sum_{j=1}^N \tau_{jt}/N$ the average subsidy.

To finance these expenditures, the government levies a tax on production, at the rate $\tau_t^f \geq 0$, or can issue debt B_t. Since capital and public debt are perfectly substitutable assets, they face the same return. Hence, debt reimbursement from the previous period is given by $r_t B_{t-1}$. The intertemporal budget constraint for the government, therefore, satisfies for all $t \geqslant 0$:

$$B_t = r_t B_{t-1} + G_t + \tau_t N - \tau_t^f Y_t \tag{11}$$

with $B_{-1} \geq 0$ given.

3 | INTERTEMPORAL EQUILIBRIUM

On the labor market, we recall that each adult agent supplies inelastically one unit of labor, but only healthy people are able to work. This means that at equilibrium, we have $L_t = H_t$. We deduce that:

$$\sum_{j=1}^{N} \Omega_{jt} = w_t L_t = w_t H_t. \tag{12}$$

We define debt and capital per adult as $b_t \equiv B_t/N$ and $k_t \equiv K_t/N$. Production per adult is given by $Y_t/N = A(h_t)a_t^s h_t$, with $a_t = k_t/h_t$. Then, using (9), the government budget constraint (11) rewrites:

$$g_t = b_t - r(a_t)b_{t-1} - \tau_t + \tau_t^f A(h_t)a_t^s h_t. \tag{13}$$

Equilibrium on the asset market is ensured by $k_{t+1} + b_t = \sum_{j=1}^{N} \sigma_{jt}/N$. We use (8), (10), (12), and $k_{t+1} = a_{t+1}h_{t+1}$ to get:

$$a_{t+1}h_{t+1} + b_t = \frac{\beta(h_{t+1})}{1 + \beta(h_{t+1})}(w(a_t)h_t + \tau_t). \tag{14}$$

Since $p_t = \alpha Y_t/N$, Equation (1), that describes the dynamics of healthy people, rewrites:

$$h_{t+1} = h_t + (1 - h_t)\Big[\gamma - \theta\Big[g_t/\Big(\alpha A(h_t)a_t^s h_t\Big)\Big]h_t\Big] \tag{15}$$

with $\theta\Big[g_t/\Big(\alpha A(h_t)a_t^s h_t\Big)\Big](1 - h_t) < 1$ under Assumption 1.

By inspection of Equation (13), we now define which policy parameters will be considered as fixed and will be used to conduct comparative statics.

Assumption 2. $b_t = b \geqslant 0$, $\tau_t = \tau \geqslant 0$, with $b > \tau$, and $\tau_t^f = \tau^f \in (0, 1)$ are constant for all $t \geqslant 0$.

The subsidy to adult and the tax rate are considered as constant, as well as debt per capita. This implicitly means that debt sustainability is not an issue or debt is always fixed at a level which is sustainable. Moreover, Assumption 2 enforces that debt per capita is high enough with respect to the average subsidy supporting adults income.

Then, public spending will vary to satisfy the government budget constraint:

$$g_t = b(1 - r(a_t)) - \tau + \tau^f A(h_t)a_t^s h_t \equiv g(a_t, h_t) \tag{16}$$

which is an increasing function in a_t and h_t. Public expenditures are thus procyclical. In case of strong epidemics, we could a priori observe a decrease in a_t and/or h_t, and therefore of public spending. Then, public debt could be used to maintain a sufficient level of public spending if debt emission is higher than debt reimbursement.

Considering this last equation and Assumption 2, an intertemporal equilibrium is a sequence (h_t, a_t) satisfying Equations (14) and (15) for all $t \geqslant 0$, that is,

$$h_{t+1} = h_t + (1 - h_t)\Big[\gamma - \theta\Big[g(a_t, h_t)/\Big(\alpha A(h_t)a_t^s h_t\Big)\Big]h_t\Big], \tag{17}$$

$$a_{t+1}h_{t+1} + b = \frac{\beta(h_{t+1})}{1 + \beta(h_{t+1})}\Big[(1 - \tau^f)(1 - s)A(h_t)a_t^s h_t + \tau\Big], \tag{18}$$

with $\theta\Big[g(a_t, h_t)/\Big(\alpha A(h_t)a_t^s h_t\Big)\Big](1 - h_t) < 1$.

Note that both h_t and $a_t = k_t/h_t$ are predetermined variables, with initial conditions $h_0 = H_0/N > 0$ and $a_0 = K_0/H_0 > 0$.

Our model highlights multiple important interplays between the real-side of the economy and epidemics. On the one side, epidemic affects labor supply, and therefore labor income. On the other side, economic activity affects the evolution of epidemic by determining the amount of public health spending, but also the level of pollution. In addition, our model also emphasizes relevant properties characterizing the consequences of epidemics: the productivity of workers lowers in case of epidemic outbreak and we observe a damaging effect on longevity, what affects negatively the saving rate.

4 | STEADY STATES WITH AND WITHOUT EPIDEMIC OUTBREAK

A steady state corresponds to a long-term equilibrium in which the share of infected people $1-h$ and the capital-labor ratio a are stationary. A steady state is a solution (h, a) satisfying:

$$(1-h)[\gamma-\theta[g(a,h)/(\alpha A(h)a^s h)]h]=0, \tag{19}$$

$$ah+b=\frac{\beta(h)}{1+\beta(h)}[(1-\tau^f)(1-s)A(h)a^s h+\tau] \tag{20}$$

with

$$g(a,h)=b[1-(1-\tau^f)A(h)sa^{s-1}]-\tau+\tau^f A(h)a^s h \tag{21}$$

and

$$\theta[g(a,h)/(\alpha A(h)a^s h)](1-h)<1. \tag{22}$$

By direct inspection of Equation (19), we distinguish two types of steady states. Some are characterized as states with infected people, $h<1$, and the others as states with only healthy-susceptible-people, $h=1$.

We focus first on states with infected people. From (19), a steady-state with $h<1$ satisfies:

$$\gamma=\theta[g(a,h)/(\alpha A(h)a^s h)]h. \tag{23}$$

Using (21), we easily get:

$$\frac{g}{p}=\frac{g(a,h)}{\alpha A(h)a^s h}=\frac{b-\tau}{\alpha Aha^s}-\frac{b(1-\tau^f)s}{\alpha ha}+\frac{\tau^f}{\alpha}\equiv\eta(h,a) \tag{24}$$

with $A=1$ if $h>\underline{h}$. Therefore, Equation (23) rewrites:

$$\gamma=\theta(\eta(h,a))h=\theta\left[\frac{b-\tau}{\alpha Aha^s}-\frac{b(1-\tau^f)s}{\alpha ha}+\frac{\tau^f}{\alpha}\right]h\equiv Z(h,a). \tag{25}$$

In the following, we assume that there is a primary deficit independently of the subsidy τ. Whatever the public support to workers, we consider that the amount of public health spending exceeds tax revenues at least when there is an epidemic outbreak, $g>\tau^f Aha^s$. Using the steady-state value for g given in Equation (21), this corresponds to the inequality $(b-\tau)a^{1-s}>b(1-\tau^f)sA$, which also ensures $\eta(h,a)>0$. We thus have:

Assumption 3. $a > \left[\frac{b(1-\tau^f)sA}{b-\tau}\right]^{\frac{1}{1-s}} \equiv \underline{a}$.

A steady state with $h < 1$ also satisfies Equation (20):

$$F(h,a) \equiv ah + b - \frac{\beta(h)}{1+\beta(h)}[(1-\tau^f)(1-s)A(h)a^s h + \tau] = 0 \tag{26}$$

with $A(h) = 1$ if $h > \underline{h}$ and $A(h) = A$ if $h < \underline{h}$.

Lemma 1. *Equation (25) implicitly defines a function $h = H_1(a)$ which is increasing for $\underline{a} < a < \hat{a}$ and decreasing for $a > \hat{a}$, with*

$$\hat{a} \equiv \left[\frac{b(1-\tau^f)A}{b-\tau}\right]^{\frac{1}{1-s}} > \underline{a}.$$

The maximum value taken by this function is given by $\widehat{h} = H_1(\hat{a})$. We also have that $H_1(\underline{a}) = H_1(+\infty) = \gamma/\theta(\tau^f/\alpha)$ and $H_1(a) \geqslant \gamma/\theta(\tau^f/\alpha)$.

Equation (26) implicitly defines a function $h = H_2(a)$ which is strictly increasing for all $a > \underline{a}$. Moreover, we have $H_2'(a) = -\frac{\partial F}{\partial a}/\frac{\partial F}{\partial h}$ which is increasing in A meaning that when h crosses $\underline{h}$, A becomes equal to 1 and the slope increases.

Proof. See Appendix A. □

Before examining in details existence and uniqueness of a steady-state with $h < 1$, we focus on disease-free steady states. A solution $h = 1$ satisfies Equation (19). It also implies that $A(h) = 1$. Therefore, Equation (20) rewrites:

$$F(1,a) = a - \frac{\beta(1)}{1+\beta(1)}(1-\tau^f)(1-s)a^s + b - \frac{\beta(1)}{1+\beta(1)}\tau = 0 \tag{27}$$

and allows to identify directly the existence of steady states with $h = 1$.

Proposition 1. *Under Assumptions 1–3 and*

$$A\frac{b}{b-\tau} < \frac{\beta(1)}{1+\beta(1)}\frac{1-s}{s} \tag{28}$$

there exists $b_1 > 0$ such that for all $b < b_1$, there is a unique disease-free steady state, $(a_1, 1)$, which always satisfies inequality (22).

Proof. See Appendix B. □

Assuming that b is not too large, the crowding-out effect of public debt is not too high. Moreover, inequality (28) ensures that savings allowing to finance public debt and to invest in productive capital is sufficiently high. Under these conditions, there exists a steady state in which all the population is healthy and the level of capital is high.

We now analyze endemic steady states, characterized by infected people $h < 1$. Based on Lemma 1, steady states with $h < 1$ are solution satisfying $h = H_1(a) = H_2(a)$. As previously mentioned, when the number of infected people is too high ($h < \underline{h}$), the economy observes an epidemic outbreak that reduces the productivity of factor $A(h)$. We thus examine the existence of steady states with such properties ($h < \underline{h} < 1$) which will coexist with the steady-state without infected, $(a_1, 1)$.

Since $H_1(a)$ is single-peaked, a steady-state with $h < 1$ is characterized by $h < \bar{h}$ if the sufficient condition $\widehat{h} < \underline{h}$ holds. From (25), $\widehat{h}$ is a solution of:

$$h = \frac{\gamma}{\theta(\eta(h, \widehat{a}\,))}. \tag{29}$$

Substituting $\widehat{a} = \left[\frac{b(1-\tau^f)A}{b-\tau}\right]^{\frac{1}{1-s}}$ in (24), we get:

$$\eta(h, \widehat{a}\,) = \frac{(1-s)}{\alpha h(1-\tau^f)^{\frac{s}{1-s}} A^{\frac{1}{1-s}}}\left(\frac{b-\tau}{b}\right)^{\frac{1}{1-s}} b + \frac{\tau^f}{\alpha} \tag{30}$$

which is a decreasing function of h.

The left-hand side of (29) is of course increasing in h from 0 to 1, while the right-hand side is decreasing in h from a positive value when $h = 0$. Therefore, if $\underline{h} > \frac{\gamma}{\theta(\eta(\underline{h}, \widehat{a}\,))}$, the value $\widehat{h}$ which solves (29) belongs to $(0, \underline{h}\,)$ and a steady-state with infected people is always marked by the epidemic outbreak. Let us assume:

Assumption 4. $\underline{h}\,\theta(\eta(\underline{h}, \widehat{a}\,)) > \gamma$.

We show the following result (see also Figure 1):

Proposition 2. *Under Assumptions 1–4,*

$$\frac{b}{b-\tau} < \frac{\beta(\gamma/\theta(\tau^f/\alpha))}{1+\beta(\gamma/\theta(\tau^f/\alpha))}\frac{1-s}{s} \quad \text{and} \quad \theta(\tau^f/\alpha) < 1 + \gamma \tag{31}$$

there exist $b_2 > 0$ and $\underline{\alpha}$ such that if $b < b_2$ and $\alpha > \underline{\alpha}$, there is a unique steady-state (a_2, h_2), with $\underline{a} < a_2 < \widehat{a}$ and $h_2 < \underline{h} < 1$, characterized by a positive share of infected people and with the epidemic outbreak.

This steady-state coexists with the one with no infected people, $(a_1, 1)$, and is characterized by a lower capital-labor ratio. We have the following ranking: $\underline{a} < a_2 < a_1 < \widehat{a}$.

Proof. See Appendix C. ☐

We notice that conditions (31) and $b < b_2$ both ensure the existence of a steady-state with epidemic outbreak that coexists with the one with no infected people.[9] A level of debt not too

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[9] Note that this inequality (31) is more stringent than inequality (28).

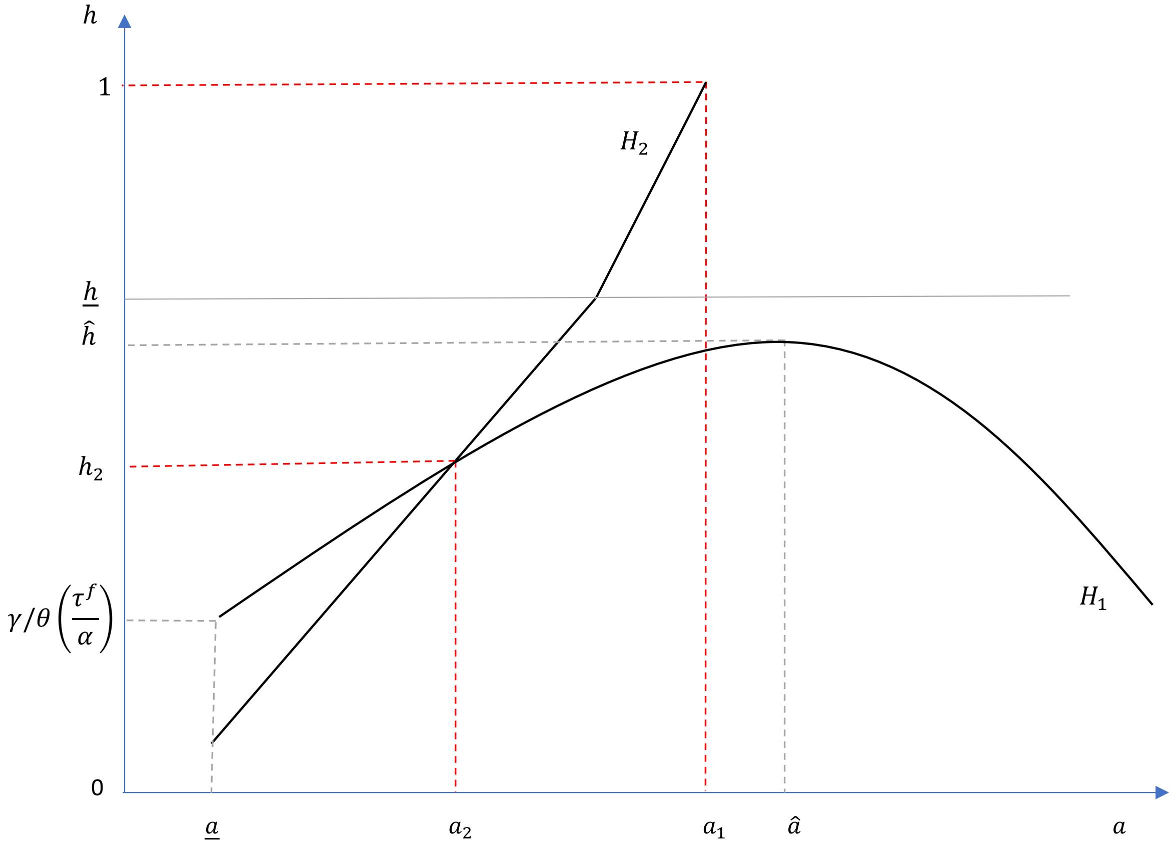

FIGURE 1 Steady states with epidemics outbreak (a_2, h_2) and no infected people $(a_1, 1)$

high associated to a high enough saving rate maintains a sufficient level of saving. The inequality $\alpha > \underline{\alpha}$, which means a sufficiently high pollution rate, ensures that $\theta(\eta(h, a))$ does not strongly depend on the capital-labor ratio. This ensures the uniqueness of the steady-state because $H_1(a)$ is not too steep (see Figure 1).

We note that the existence of both steady states requires a level of debt not too significant. This is due to the fact that one channel through which debt intervenes on the equilibrium goes through savings. Part of savings is devoted to finance public debt. Therefore, if debt is too large, the level of savings is no more sufficient to sustain a positive level of capital, which may rule out the existence of any steady-state.

We pay particular attention to the effect of a variation in the productivity parameter A on the endemic steady state. A decrease or a sufficiently low level of A can be seen as the economic impacts of a virulent pandemic, which induce strong disorganization of labor. In such a period, there is not only lower productivity or efficiency of labor, but also of capital, because some machines have to be stopped for instance. Therefore, we analyze now in more details the effect of a variation of A on h_2 and a_2, that is, what happens if the loss of productivity is even more severe:

Proposition 3. *Under Assumptions 1–4, inequality (31), $\theta(\tau^f/\alpha) < 1 + \gamma$, $\alpha > \underline{\alpha}$ and $b < b_2$, following a slight increase of the productivity A, the sign of the variation of h_2 is indeterminate.*

Moreover, there exist $\overline{\alpha}_A$ and $\underline{\alpha}_A (\leqslant \overline{\alpha}_A)$ such that a slight increase of A implies an increase of a_2 for $\alpha > \max\{\underline{\alpha}, \overline{\alpha}_A\}$ and a decrease of a_2 for $\underline{\alpha}_A > \alpha > \underline{\alpha}$ and A low enough.

Proof. See Appendix D. ☐

The fall in the productivity parameter A implies opposite effects on the transmission rate θ. Through this direct effect of A, pollution decreases more than public spending, which means that the transmission rate θ goes down.

Lower productivity also implies a fall in income that reduces savings and hence capital-labor ratio if α is high enough. Indeed, in this case, the positive effect of a fall in A on savings, that goes through the reduction of θ, is not sufficient to compensate for the negative income effect. Since a lower capital-labor ratio also means lower public spending relative to pollution, the transmission rate θ goes up through this channel. These two competing effects on θ explain that the effect of A on the proportion of healthy people h_2 is not so clear-cut.

The endemic steady state depends also on pollution intensity of production, captured by α, as it modifies the transmission rate of epidemics. When α goes up, so does θ: epidemic spreads more easily. Examining Figure 1, the curve $H_1(a)$ shifts downward, whereas $H_2(a)$ is not affected: both a_2 and h_2 fall. A higher pollution intensity is thus damaging for the economy as it increases the transmission rate of epidemics and therefore the number of infected people. This negatively affects both the labor income and the saving rate $(\beta(h)/(1+\beta(h)))$, which reduces capital investment along the steady-state with epidemic outbreak. Therefore, any environmental policy or technological progress that aims to reduce the pollution rate is useful. It decreases the proportion of infected people, through a lower transmission rate. But interestingly, it will also raise capital and production. We are not able to quantify the precise impact of such policy measures on economic variables, but this type of environmental improvement can at least been considered as a tool accompanying an appropriate fiscal policy.

5 | CONVERGENCE TO ENDEMIC OR DISEASE-FREE STEADY STATE

We analyze the issue of convergence by studying the local stability properties of the two steady states $(a_1, 1)$ and (a_2, h_2). Using Assumption 1, Equations (17) and (18) rewrite:

$$h_{t+1} = h_t + (1 - h_t)[\gamma - \theta(\eta(h_t, a_t))h_t] \tag{32}$$

$$a_{t+1}h_{t+1} + b = \frac{\beta(h_{t+1})}{1 + \beta(h_{t+1})}\left[(1 - \tau^f)(1 - s)Aa_t^s h_t + \tau\right] \tag{33}$$

where $A = 1$ if $h_t > \underline{h}$ and $\eta(h_t, a_t)$ is given by Equation (24). We also keep in mind that this two-dimensional dynamic system involves two predetermined variables, h_t and $a_t = k_t/h_t$. Differentiating these two equations in the neighborhood of a steady state, we get:

$$dh_{t+1} = J_{hh}dh_t + J_{ha}da_t \tag{34}$$

$$da_{t+1} = J_{ah}dh_t + J_{aa}da_t \tag{35}$$

where the terms J_{ii} are the elements of the associated Jacobian matrix given by:

$$J_{hh} = 1 - \gamma + \theta(\eta)h - (1 - h)\left[\theta(\eta) + h\theta'(\eta)\frac{\partial \eta}{\partial h}\right] \tag{36}$$

$$J_{ha} = -(1-h)h\theta'(\eta)\frac{\partial \eta}{\partial a} \tag{37}$$

$$\begin{aligned} J_{ah} = {} & \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)A\frac{a^s}{h} - \left[\frac{a}{h} - \frac{\beta'(h)}{h(1+\beta(h))^2}((1-\tau^f)(1-s)Aa^sh+\tau)\right] \\ & \left[1-\gamma+\theta(\eta)h-(1-h)\left[\theta(\eta)+h\theta'(\eta)\frac{\partial \eta}{\partial h}\right]\right] \end{aligned} \tag{38}$$

$$\begin{aligned} J_{aa} = {} & \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1} + \left[\frac{a}{h} - \frac{\beta'(h)}{h(1+\beta(h))^2}((1-\tau^f)(1-s)Aa^sh+\tau)\right] \\ & (1-h)h\theta'(\eta)\frac{\partial \eta}{\partial a} \end{aligned} \tag{39}$$

with $\eta = \eta(h, a)$. Substituting $h = 1$ in these equations, we easily obtain:

Proposition 4. *Under Assumptions 1–4, inequality (28) and $b < b_1$, the steady-state with no infected people, $(a_1, 1)$, is a saddle because $\theta(\eta_1) > \gamma$, where $\eta_1 \equiv \eta(1, a_1)$.*

Proof. See Appendix E. □

Under Assumption 4, the steady-state with no epidemics is a saddle. Hence, since the two dynamic variables are predetermined, the economy cannot converge toward a steady-state without infected people. Indeed, the dynamics of the capital-labor ratio, which is governed by the equilibrium between capital investment and savings, is stable. However, under Assumption 4, the transmission rate exceeds the recovery rate at the disease-free steady states. Then, the evolution of healthy people is unstable, which explains that one cannot converge to this steady-state with no epidemics.

We focus now on the dynamics around the steady-state (a_2, h_2) characterized by $h_2 < 1$.

Proposition 5. *Under Assumptions 1–4, inequality (31), $\alpha > \underline{\alpha}$ and $b < b_2$, there exits $\widetilde{\beta}'(1) > 0$ such that the steady-state (a_2, h_2) is stable for $\beta'(1) > \widetilde{\beta}'(1)$.*

Proof. See Appendix F. □

The endemic steady state is the only one which is stable. This means that the economy should converge to this steady-state rather than toward the steady-state with no infected people. As a direct implication, under our current assumptions, epidemics will persist and will not collapse even in the long run.

We notice that the condition $\alpha > \underline{\alpha}$ is the one that ensures the uniqueness of the steady-state with epidemic outbreak (see Proposition 2).[10] Of course, it promotes the stability of the steady-state. Convergence toward the steady-state with epidemic outbreak requires $\beta'(1)$ high enough, that is, the longevity is sufficiently sensitive to the share of healthy people.[11] Taking into account the dynamic equations (32) and (33), consider an increase in h_t and a_t. This induces an important increase in labor income, savings and hence future capital. At the same

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[10] It excludes any bifurcation (pitchfork) associated to an eigenvalue that would cross the value one.

[11] This is a sufficient condition that excludes the occurrence of a flip bifurcation whatever the value of $\theta'(\eta)$. It does not mean that a flip bifurcation could occur otherwise. For instance, if $\theta'(\eta)$ is sufficiently weak in absolute value, such a bifurcation is always excluded. In any case, we are not interesting in the existence of endogenous cycles in this paper.

time, these raises may favor a higher transmission rate θ_t, which dampens the positive dynamics for h_t. When agent's longevity is highly sensitive to an improvement of the health condition in the economy, the increase in savings is dampened which prevents capital accumulation to be explosive. Rather, the economy converges to a stationary long-run equilibrium with epidemic outbreak.

6 | THE ROLE OF FISCAL POLICY

The fiscal instruments seem to play a crucial role on the existence of both steady states and their stability properties, through their impacts on the transmission rate which depends on public spending. The question is therefore to know if a modification of the fiscal policy could improve the health and macroeconomic situation described until now. We investigate first whether following an appropriate choice of the level of debt b and transfer τ, the existence of the steady-state with epidemic outbreak (a_2, h_2) can be ruled out and the economy may rather converge to the steady-state without epidemics.

Considering that Assumption 4 is not satisfied, that is, $\underline{h}\,\theta(\eta(\underline{h}, \hat{a}\,)) < \gamma$, we show in the following proposition that the steady-state with epidemic outbreak may be ruled out while the steady-state with no infected people becomes stable.

Proposition 6. *Under Assumptions 1–3,* $\underline{h}\,\theta(\eta(\underline{h}, \hat{a}\,)) < \gamma$, $\alpha > \underline{\alpha}$ *and*

$$\frac{b}{b-\tau} < \min\left\{\frac{\beta(\gamma/\theta(\tau^f/\alpha))}{1+\beta(\gamma/\theta(\tau^f/\alpha))}\frac{1-s}{s}; \frac{\beta(1)}{1+\beta(1)}\frac{1-s}{A}\right\} \tag{40}$$

there exits $b_b > 0$ *such that for* $b < b_b$*, the steady-state* (a_2, h_2) *does no more exist while the steady-state* $(a_1, 1)$ *is stable.*

Proof. See Appendix G. ☐

This proposition shows that for an appropriate choice of debt b and transfer τ, the economy can enter in a configuration where there is only one existing steady-state, the one without epidemics and infected people. Figure 2 illustrates the proposition.

In addition, this unique steady state is stable because the transmission rate is now lower than the rate of recovery, which implies that the share of infected people converges to zero. This means that the economy might converge toward the long-run disease-free equilibrium.

For an agent who was already healthy, converging to such a steady state instead of being at an endemic one is a source of higher welfare because his income raises. This can be dampened by the decrease of interest rate which reduces the return of debt used to consume when old and by the decrease of the share of income consumed $1/(1+\beta(h))$ (see Equations 6 and 7). For an infected people, which becomes healthy at a disease-free steady state, the increase of income is even larger because her labor supply increases. As a result, moving from the endemic to the disease free steady state improves welfare as long as the income gains are sufficiently important.

The results of Proposition 6 requires that the transmission rate is sufficiency low, $\underline{h}\,\theta(\eta(\underline{h}, \hat{a}\,)) < \gamma$, that is, $\eta(\underline{h}, \hat{a}\,)$ not too low. By direct inspection of (30), we observe that it is possible if either b or $(b-\tau)/b$ are not too close to 0, taking into account that the pollution rate

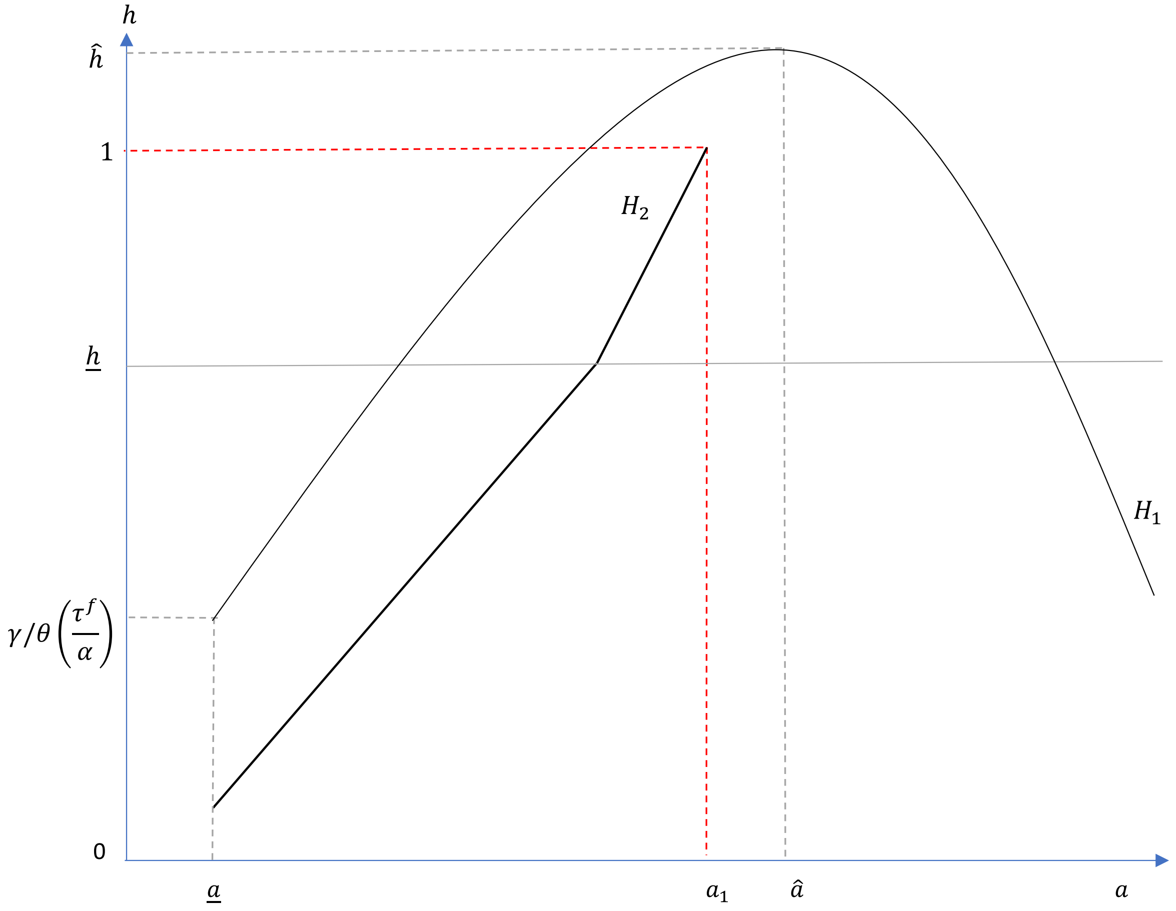

FIGURE 2 Steady state with no infected people $(a_1, 1)$

α is not too high. Debt has to be positive but not too important to remove the unfavorable situation in which the economy converges to a steady-state with epidemics. Of course, as already mentioned after Proposition 2, if the level of debt is too high, the two steady states are ruled out and the economy surely collapses because it is not possible to sustain investment in capital that does not converge to zero. Another unfavorable policy corresponds to the situation where, in contrast to Proposition 6, Assumption 4 holds but the level of debt rules out the existence of the endemic steady state. In such a configuration, the disease-free steady state still exists but is unstable, which means that the public policy is not able to improve the health and economic situations.

Focusing on the results of Proposition 6, public debt has a crowding-out effect on capital because part of savings is used to finance it. At the steady-state with epidemic outbreak, h is of course lower than at the disease-free steady state. This means that both the labor income and the saving rate $\beta(h)/(1+\beta(h))$ are lower. As a result, for a given level of debt, the share of savings devoted to finance public assets is larger at the steady-state with epidemic outbreak. This explains that there are levels of debt such that savings can no more sustain a positive level of capital with epidemic outbreak, whereas it is still possible at the disease-free steady state.

If the government has not the degree of freedom to set its fiscal instruments such that Assumption 4 will be violated, public policy cannot be managed to achieve a transition toward the disease-free steady state. In such a context, the question is rather to know what can improve the features of the stable endemic steady state. Accordingly, we examine now how, under Assumption 4, the government can manage its policy instruments, in particular its public debt b

and tax τ^f, to increase the steady-state values with epidemic outbreak, namely a_2 and h_2. Let us focus first on a variation of debt b:

Proposition 7. *Under Assumptions 1–4, inequality (31), $\theta(\tau^f/\alpha) < 1+\gamma$, $\alpha > \underline{\alpha}$, $\beta'(1) > \widetilde{\beta}'(1)$, and $b < b_2$, there exists $b_3 > 0$ such that following a slight increase of debt, h_2 increases if $b < b_3$.*

Moreover, there exists $\widetilde{\alpha} > 0$, $\overline{\alpha} > 0$ and $b_4 > 0$ such that a slight increase of debt implies a decrease of a_2 for $\alpha > \max\{\underline{\alpha}, \widetilde{\alpha}\}$ and an increase of a_2 for $\underline{\alpha} < \alpha < \overline{\alpha} (\leqslant \widetilde{\alpha})$ and $b < b_4$.

Proof. See Appendix H. ☐

Debt increase affects positively h as it allows to increase public spending. This tends to reduce the transmission rate of epidemics. However, at the same time, it might reduce the capital-labor ratio and, hence, increases the cost of debt, which affects negatively the amount of public spending devoted to health. This last effect on the transmission rate is dampened by a negative effect of the capital-labor ratio reduction on pollution. When debt is not too important, the possible negative effect is not too high and the net effect of the debt variation on h is positive.

The debt increase entails competing effects on the capital-labor ratio. On the one hand, it has a negative effect on capital accumulation through a standard crowding-out effect. On the other hand, a higher level of debt allows to increase public health spending, to reduce the transmission rate of epidemics and hence to increase the share of healthy people. This tends to favor capital accumulation in the economy as it increases the labor income and the saving rate, which depends positively on the share of healthy people through the longevity β. Hence, we highlight a new mechanism through which debt can finally have a crowding-in effect on capital.

As regards the crowding-in effect, it is dampened if the pollution rate is sufficiently high. In such a case, the increase of the share of healthy people through the reduction of the transmission rate is too low. To summarize, the crowding-out effect dominates when α is high, but there is a positive effect of debt on the capital-labor ratio if b is not too high and α has an intermediate value. Of course, when longevity is highly sensitive to the health condition, the critical value of α under which the crowding-in effect of the debt dominates is larger.

Note that the existence of $b_4 > 0$ requires $\tau > 0$. A positive average transfer allows to define a policy favorable to capital accumulation. The increase in h entailed by an increase in government debt leads to a higher positive effect on savings when households' incomes are subsidized. The increase in savings generated by a higher longevity is more important when the government makes high-income transfers.

When a debt increase affects positively the share of healthy people and the capital stock, the positive effect on production is clear cut, and we can conjecture a positive effect on welfare. Using (25) and (26), we can also easily conjecture that a decrease of the average lump-sum subsidy τ will have the same effect than an increase of public debt.

We now address the effect of a variation of the product tax rate on the endemic steady state:

Proposition 8. *Under Assumptions 1–4, inequality (31), $\theta(\tau^f/\alpha) < 1+\gamma$, $\alpha > \underline{\alpha}$, $\beta'(1) > \widetilde{\beta}'(1)$, and $b < b_2$, there exists $b_5 > 0$ such that following a slight increase of the tax rate on production τ^f, h_2 increases for $b < b_5$.*

Moreover, there exist $\tilde{\alpha}_\tau > 0$ *and* $\bar{\alpha}_\tau > 0$ *such that a slight increase of* τ^f *implies a decrease of* a_2 *for* $\alpha > \max\{\underline{\alpha}, \tilde{\alpha}_\tau\}$ *and an increase of* a_2 *for* $\underline{\alpha} < \alpha < \bar{\alpha}_\tau (\leqslant \tilde{\alpha}_\tau)$ *and* τ *close to* b.

Proof. See Appendix I. ☐

The effects of a variation of τ^f and b on the steady-state with epidemics are very similar. On the one hand, an increase of the tax rate increases the amount of public health funds available, g, which reduces the transmission rate of epidemics, even if the capital-labor ratio becomes lower. This raises the share of healthy people, and therefore labor. It improves aggregate savings and hence capital accumulation, through higher labor income and saving rate. On the other hand, a higher tax reduces available income, which has a negative effect on the amount of savings. The first effect of the tax rate, which is positive, is the dominant one if the pollution rate α takes intermediate values and the average subsidy τ is sufficiently high and close to the level of debt b to ensure a high enough income.

On the contrary, the second effect, which is negative, dominates when the pollution rate α is high enough. In this case, pollution is important, the transmission rate higher and the labor force h smaller. The fall in savings entailed by the tax τ^f is highly costly since the variation of healthy worker is quite weak and this policy instrument will not be efficient to increase a_2.

Although the effect of a variation of τ^f and b are similar, it is important to note that both instruments are not perfect substitute. While public debt decreases the share of saving allocated to private assets without affecting directly the amount of saving, production tax has a direct effect on saving. The negative effect of τ^f thus depends on the saving rate. The condition to have a policy favorable for a_2 requires τ close to b. This implies a low level of government spending g and hence a high transmission rate θ. In such a case, saving rate is sufficiently low, so does the negative effect of τ^f.

7 | TRANSFERS TO ADDRESS INEQUALITIES BETWEEN HEALTHY AND INFECTED AGENTS

In our model, epidemics create inequality. Indeed, at the endemic steady state, we can distinguish two groups of individuals that have heterogeneous income profile. People are either healthy at adult age, able to work and hence earn a wage, or are infected at adult age and receive only the lump sum subsidy. Government can put in place a transfer program for redistribution motives. We address this question in the section.

Substituting the two expressions of consumptions (6) and (7) in the utility function (3), we get the agents j welfare:

$$W_{jt} \equiv \beta(h_{t+1})\ln r_{t+1} + (1 + \beta(h_{t+1}))[\ln(\Omega_{jt} + \tau_{jt}) - \ln(1 + \beta(h_{t+1}))]. \tag{41}$$

As Ω_{jt} is equal to the labor income for healthy and zero for infected, the subsidies τ_{jt} can be used to correct inequality and ensure the same welfare for both kind of agents.

Using (41), at the endemic steady state (a_2, h_2), the difference between the welfare of a healthy $(j = H)$ and an infected $(j = I)$ individual is given by:

$$W_H - W_I = (1 + \beta(h_2))[\ln(w(a_2) + \tau_H) - \ln \tau_I]$$

where τ_H is the subsidy distributed to each healthy individual and τ_I the one distributed to each infected people. Then, the welfare is the same for all people if $W_H = W_I$, which is equivalent to:

$$\tau_I - \tau_H = w(a_2) = (1 - \tau^f)A(1 - s)a_2^s \tag{42}$$

Given the values of the average subsidy τ and the share of healthy agents h_2, the transfer system, τ_H and τ_I, is constrained and should satisfy:

$$\tau = h_2\tau_H + (1 - h_2)\tau_I \tag{43}$$

Note that using (42), we have $\tau_I = \tau_H + w(a_2)$. Substituting τ_I in Equation (43), we obtain $\tau = \tau_H + (1 - h_2)w(a_2) < \tau_H + w(a_2)$. Since $\tau \geqslant 0$, this means that the income received by each agent is identical and positive.

This result is summarized in the following proposition.

Proposition 9. *Under Assumptions 1–4, inequality (31), $\theta(\tau^f/\alpha) < 1 + \gamma$, $\alpha > \underline{\alpha}$, $\beta'(1) > \widetilde{\beta}'(1)$ and $b < b_2$, all individuals have the same welfare at the endemic steady state (a_2, h_2) if τ_H and τ_I satisfy Equations (42) and (43).*

This proposition shows that once the policy parameters b, τ^f, and τ are fixed to determine the levels of a_2 and h_2, the two levels of subsidy τ_H and τ_I can be used to equalize the levels of income and welfare of healthy and infected people. Two subsidies different from zero are required to be able to fix the redistribution policy independently of the level of the average subsidy τ and of the stationary levels a_2 and h_2. An income redistribute policy in favor of infected $\tau_I > \tau_H$ is a way to avoid inequality generated by epidemics. Note that such policy could come at an additional cost for healthy people. When public budget for transfer τ is low enough, healthy individuals becomes a taxpayer ($\tau_H < 0$). To tackle inequality due to epidemics without reducing income profile of healthy people, government should devote a large amount of fund to transfer policy. This has to come with an increase in debt.

To sum up, we show that in case of epidemics, the fiscal policy can be used first to rule out any endemic steady-state and promote the convergence to a stable long-run equilibrium with no epidemics. If the implementation of such a policy is not possible, we argue that a government should try to improve the situation at a stable endemic steady state. We show that this is possible by raising debt or increasing the fiscal pressure if associated public spending are used to improve health care. Another novelty of this paper is to underline that the effectiveness of these policies strongly depends on the level of pollution, which is linked to the production technology. Finally, if the economy converges to the steady-state where healthy and infected individuals coexist, it is possible to redistribute income between individuals with an appropriate choice of subsidies to rule out welfare inequalities.

8 | CONCLUSION

In this paper, we examine the interplay between epidemics, pollution, and fiscal policies in a macroeconomic framework. The health impacts of the infection depend on the pollution intensity and on the age profile of the agent. To take into account these features, we study the dynamics of epidemics in an OLG model where fiscal instruments are used to fight the health and macroeconomic consequences of the disease. We emphasize situations in which the transmission rate of epidemics exceeds the recovery rate, implying that the economy cannot achieve a disease-free state. Public debt and income transfers may address such unfavorable situations. We determine some fiscal policies that allow the economy to converge to a state without infected people and with a higher level of capital. In a context in which public policy is not able to eradicate the epidemic, it could however be used to reduce the number of infected people and increase capital per capita in the long run. In an economy where a public health policy is not sufficient to eradicate the epidemics, a fiscal policy with public debt is an appropriate tool for living with the epidemic, keeping the number of infected people at a stationary, and potentially low, level. It requires, however, a not too high pollution intensity. This result thus highlights the potential role of environmental policies to prevent and fight efficiently infectious diseases. Finally, a redistribution using subsidies to households is recommended to reduce or even rule out welfare inequalities.

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APPENDIX A: PROOF OF LEMMA 1

A steady-state with $h < 1$ satisfies Equations (25) and (26). Using (24), we obtain the following derivatives:

$$\frac{\partial \eta}{\partial h} = \frac{b(1-\tau^f)sA - (b-\tau)a^{1-s}}{\alpha A h^2 a} \tag{A1}$$

$$\frac{\partial \eta}{\partial a} = s\frac{b(1-\tau^f)A - (b-\tau)a^{1-s}}{\alpha A h a^2} \tag{A2}$$

Under Assumption 3, we have $\partial\eta/\partial h < 0$ and there exists $\hat{a} \equiv \left[\frac{b(1-\tau^f)A}{b-\tau}\right]^{\frac{1}{1-s}} > \underline{a}$ such that $\partial\eta/\partial a > 0$ for $a < \hat{a}$ and $\partial\eta/\partial a < 0$ for $a > \hat{a}$. Therefore, Equation (24) implicitly defines a function $h = H_1(a)$ which is increasing for $\underline{a} < a < \hat{a}$ and decreasing for $a > \hat{a}$. The maximum value taken by this function is given by $\widehat{h} = H_1(\hat{a})$. We also have $\eta(h, \underline{a}) = \eta(h, +\infty) = \tau^f/\alpha$. We deduce that $H_1(\underline{a}) = H_1(+\infty) = \gamma/\theta(\tau^f/\alpha)$ and $H_1(a) \geqslant \gamma/\theta(\tau^f/\alpha)$.

Then, differentiating Equation (26), we obtain:

$$\frac{\partial F}{\partial h} = a - \frac{\beta'(h)}{(1+\beta(h))^2}[(1-\tau^f)(1-s)Aa^s h + \tau] - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)Aa^s \tag{A3}$$

$$\frac{\partial F}{\partial a} = h\left[1 - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\right] \tag{A4}$$

Using (26) and (A3), we have:

$$\frac{\partial F}{\partial h}h = \frac{\beta(h)}{1+\beta(h)}\tau - b - \frac{\beta'(h)h}{(1+\beta(h))^2}[(1-\tau^f)(1-s)Aa^sh + \tau] < 0$$

Using the last equation, we note that:

$$\begin{aligned}\tfrac{\partial F}{\partial a} &> h\left[1 - \tfrac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sA\underline{a}^{\,s-1}\right]\\ &= h\left[1 - \tfrac{\beta(h)}{1+\beta(h)}(1-s)\left(1-\tfrac{\tau}{b}\right)\right] > 0\end{aligned}$$

meaning that $\frac{\partial F}{\partial a} > 0$ for all $a > \underline{a}$. Therefore, Equation (26) implicitly defines a function $h = H_2(a)$ which is strictly increasing for all $a > \underline{a}$. We note that $H_2'(a) = -\frac{\partial F}{\partial a}/\frac{\partial F}{\partial h}$ is increasing in A, which means that when h crosses $\underline{h}$, A becomes equal to 1 and the slope increases.

APPENDIX B: PROOF OF PROPOSITION 1

Under Assumption 3, we have $\frac{\beta(1)}{1+\beta(1)}\tau - b < 0$. Using (27), we can easily deduce the following:

1. If $\frac{\beta(1)}{1+\beta(1)}\tau - b$ is not too negative, there are two steady states with $a > 0$ and $h = 1$;
2. If $\frac{\beta(1)}{1+\beta(1)}\tau - b$ is sufficiently negative, there is no steady-state with $a > 0$ and $h = 1$.

Note that in the last case, the crowding-out effect of public debt is too high. Even if all the population is healthy, the transfer τ is too low to maintain a sufficient level of saving allowing to finance public debt and to invest in productive capital.

Assuming that b is not too large, we are in the configuration with two steady states. To show the existence of the steady-state with the highest level of capital, we note that $\partial^2F(1,a)/\partial a^2 > 0$ and $F(1,+\infty) > 0$. Therefore, if:

$$A\frac{s}{1-s}\frac{b}{b-\tau} < \frac{\beta(1)}{1+\beta(1)} \tag{B1}$$

there exist $b_1 > 0$ such that $F(1,\underline{a}) < 0$ for all $\tau < b < b_1$.

APPENDIX C: PROOF OF PROPOSITION 2

We examine the conditions for the existence of steady states with infected people and epidemic outbreak, that is, $h < \underline{h} < 1$. From (26), we have:

$$F(h, \hat{a}) = h\hat{a}\left(1 - \frac{\beta(h)}{1+\beta(h)}\frac{A(h)}{A}\frac{(b-\tau)(1-s)}{b}\right) + b - \tau\frac{\beta(h)}{1+\beta(h)} \tag{C1}$$

Under Assumption 4, we have $F(\hat{h}, \hat{a}) > 0$, which is equivalent to $H_2(\hat{a}) > H_1(\hat{a}) = \hat{h}$. Therefore, there exists a steady state with $h < 1$ if $H_2(\underline{a}) < H_1(\underline{a})$. From (26), we have:

$$\begin{aligned} F(\gamma/\theta(\tau^f/\alpha), \underline{a}) = {} & \frac{\gamma}{\theta(\tau^f/\alpha)}\left(\underline{a} - \frac{\beta(\gamma/\theta(\tau^f/\alpha))}{1+\beta(\gamma/\theta(\tau^f/\alpha))}(1-\tau^f)(1-s)A\underline{a}^{\,s}\right) \\ & + b - \tau\frac{\beta(\gamma/\theta(\tau^f/\alpha))}{1+\beta(\gamma/\theta(\tau^f/\alpha))} \end{aligned} \tag{C2}$$

Thus, when the following inequality:

$$\underline{a} < \frac{\beta(\gamma/\theta(\tau^f/\alpha))}{1+\beta(\gamma/\theta(\tau^f/\alpha))}(1-\tau^f)(1-s)A\underline{a}^{\,s} \Leftrightarrow \frac{b}{b-\tau}\frac{s}{1-s} < \frac{\beta(\gamma/\theta(\tau^f/\alpha))}{1+\beta(\gamma/\theta(\tau^f/\alpha))}$$

is satisfied, there exists $b_2 > 0$ such that for $b < b_2$, we have $F(\gamma/\theta(\tau^f/\alpha), \underline{a}) < 0$. As $F(\gamma/\theta(\tau^f/\alpha), \underline{a}) < 0$ is equivalent to $H_2(\underline{a}) < H_1(\underline{a}) = \gamma/\theta(\tau^f/\alpha)$, we have sufficient conditions for the existence of a steady state with $h < 1$. Note that $F(\gamma/\theta(\tau^f/\alpha), \underline{a}) < 0$ implies $F(1, \underline{a}) < 0$ because $\partial F(a, h)/\partial h < 0$, which ensures also the existence of the steady state $(a_1, 1)$.

Furthermore, we note that the steady-state $(a_1, 1)$ solves $H_2(a_1) = 1$, which is equivalent to $F(1, a_1) = 0$. Since $H_2(a)$ is an increasing function whatever the value of A, it is clear that a steady-state with $h < 1$ is always characterized by a lower level of capital-labor ratio a than a steady-state with $h = 1$. Using (C1), we further have $F(1, \hat{a}) > 0$. Since $\partial F(h, a)/\partial a > 0$, this implies that $a_1 < \hat{a}$.

Finally, we note that there is a unique steady-state with $h < 1$ if we have $H_2'(a) > H_1'(a)$ at each equilibrium satisfying $H_2(a) = H_1(a)$. Using (26) and (A4), we have:

$$H_2'(a) = \frac{h^2\left[1 - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\right]}{b - \frac{\beta(h)}{1+\beta(h)}\tau + \frac{\beta'(h)h}{(1+\beta(h))^2}[(1-\tau^f)(1-s)Aa^s h + \tau]} \tag{C3}$$

Using now (25) and (A2), we obtain:

$$H_1'(a) = \frac{-\theta'(\eta)s\frac{b(1-\tau^f)A-(b-\tau)a^{1-s}}{\alpha Aa^2}}{\theta(\eta) - \theta'(\eta)\frac{(b-\tau)a^{1-s}-b(1-\tau^f)sA}{\alpha Aha}} \tag{C4}$$

The inequality $H_2'(a) > H_1'(a)$ is thus equivalent to:

$$\begin{aligned}&\alpha A a\gamma > \theta'(\eta)[(b-\tau)a^{1-s} - b(1-\tau^f)sA]\\ &-\theta'(\eta)s\frac{b(1-\tau^f)A-(b-\tau)a^{1-s}}{ah\frac{\partial F}{\partial a}}\left[b - \frac{\beta(h)}{1+\beta(h)}\tau + \frac{\beta'(h)h}{(1+\beta(h))\beta(h)}(ah+b)\right]\end{aligned} \tag{C5}$$

Note that h and a have finite and strictly positive values. We deduce that $H_2'(a) > H_1'(a)$ for α high enough. It means that there exists $\underline{\alpha}$ such that for $\alpha > \underline{\alpha}$, there is a unique steady state (a_2, h_2) such that $h < 1$.

Finally, inequality (22) is satisfied at the steady state (a_2, h_2) if $\theta(\eta(h_2, a_2))(1-h_2) < 1$. Using (23), this is equivalent to $\theta(\eta(h_2, a_2)) < 1+\gamma$. Using Lemma 1, this is always satisfied because $\theta(\tau^f/\alpha) < 1+\gamma$.

APPENDIX D: PROOF OF PROPOSITION 3

Focusing on Equations (25) and (26) with $h < 1$, the effect of a variation of A on the endemic steady state outbreak (a_2, h_2) is given by:

$$I\begin{pmatrix} da \\ dh \end{pmatrix} + \begin{pmatrix} \partial Z/\partial A \\ \partial F/\partial A \end{pmatrix} dA = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

with

$$I = \begin{pmatrix} \partial Z/\partial a & \partial Z/\partial h \\ \partial F/\partial a & \partial F/\partial h \end{pmatrix}$$

which implies that:

$$\frac{da}{dA} = -\frac{1}{\mathrm{Det}I}\left(\frac{\partial F}{\partial h}\frac{\partial Z}{\partial A} - \frac{\partial Z}{\partial h}\frac{\partial F}{\partial A}\right)$$

$$\frac{dh}{dA} = -\frac{1}{\mathrm{Det}I}\left(-\frac{\partial F}{\partial a}\frac{\partial Z}{\partial A} + \frac{\partial Z}{\partial a}\frac{\partial F}{\partial A}\right)$$

with $-1/\mathrm{Det}I > 0$.

We first examine the effect of A on h_2, examining the sign of dh/dI, which is given by the sign of:

$$-\frac{\partial F}{\partial a}\frac{\partial Z}{\partial A} + \frac{\partial Z}{\partial a}\frac{\partial F}{\partial A} = h\theta'(\eta)\frac{b}{\alpha A^2 a^{2-s}}\left[\frac{b-\tau}{b}a^{1-s} - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)^2(1-s)sA^2\right]$$

This is strictly positive for all $a < \hat{a}$ if $\frac{b-\tau}{b}\hat{a}^{\,1-s} < \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)^2(1-s)sA^2$. This is equivalent to $\frac{b}{b-\tau} < \frac{\beta(h)}{1+\beta(h)}s(1-s)$, which is never satisfied. This is negative for all $a > \underline{a}$ if $\frac{b-\tau}{b}\underline{a}^{\,1-s} > \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)^2(1-s)sA^2$. This is equivalent to $\frac{b}{b-\tau}s > \frac{\beta(h)}{1+\beta(h)}(1-s)$, but is incompatible with inequality (31). As a result, we have no clear-cut conclusion concerning the effect of A on h.

We then examine the effect of a variation of the productivity on the stationary capital-labor ratio, da/dA. It is given by the sign of the following expression:

$$\frac{\partial F}{\partial h}\frac{\partial Z}{\partial A} - \frac{\partial Z}{\partial h}\frac{\partial F}{\partial A} = \theta'(\eta)\frac{b-\tau}{\alpha A^2 a^s h}\left[b - \frac{\beta(h)}{1+\beta(h)}\tau + \frac{\beta'(h)h}{(1+\beta(h))\beta(h)}(ah+b)\right]$$
$$+\left[\gamma + \theta'(\eta)\frac{b(1-\tau^f)sA-(b-\tau)a^{1-s}}{\alpha A a}\right](1-\tau^f)(1-s)a^s\frac{\beta(h)}{1+\beta(h)}$$

This is positive if and only if:

$$\alpha A a\gamma > \theta'(\eta)[(b-\tau)a^{1-s} - b(1-\tau^f)sA]$$
$$-\theta'(\eta)\frac{b-\tau}{(1-\tau^f)(1-s)Aa^{2s-1}h}\left[\frac{1+\beta(h)}{\beta(h)}b - \tau + \frac{\beta'(h)h}{\beta(h)^2}(ah+b)\right] \tag{D1}$$

There exist $\overline{\alpha}_A \geqslant 0$ and $\underline{\alpha}_A(\leqslant\overline{\alpha}_A)$ such that this inequality is satisfied for $\alpha > \overline{\alpha}_A$ and is not satisfied for $\alpha < \underline{\alpha}_A$.

Using (C5) and (D1), $\underline{\alpha}_A > \underline{\alpha}$ is equivalent to:

$$\frac{b-\tau}{b}\left[ah + \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^s(1-h)\right] > \frac{\beta(h)}{1+\beta(h)}s(1-s)(1-\tau^f)^2A^2 \tag{D2}$$

Using $a > \underline{a}$, this requires:

$$\left[\frac{b(1-\tau^f)s}{b-\tau}\right]^{\frac{s}{1-s}}\left[h + \frac{\beta(h)}{1+\beta(h)}(1-s)(1-h)\frac{b-\tau}{b}\right] > \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)A^{\frac{1-2s}{1-s}} \tag{D3}$$

which is satisfied if A is low enough.

APPENDIX E: PROOF OF PROPOSITION 4

Substituting $a = a_1$ and $h = 1$ in Equations (36)–(39), we note that $J_{ha} = 0$, which means that the two eigenvalues are given by:

$$J_{hh} = 1 - \gamma + \theta(\eta_1) \tag{E1}$$

$$J_{aa} = \frac{\beta(1)}{1+\beta(1)}(1-\tau^f)(1-s)sAa_1^{s-1} \tag{E2}$$

where $\eta_1 \equiv \eta(1, a_1)$. Using (A4) and the result that $\partial F/\partial a > 0$ for all $h > 0$, we easily deduce that $J_{aa} \in (0, 1)$.

Using Assumption 4, we have $1 > \underline{h} > \widehat{h} = \gamma/\theta(\eta(\widehat{h}, \widehat{a}))$. This implies that $\theta(\eta(\widehat{h}, \widehat{a})) > \gamma$. Since $\widehat{h} < 1$ and $\widehat{a} > a_1$, we deduce that $\theta(\eta_1) = \theta(\eta(1, a_1)) > \theta(\eta(\widehat{h}, \widehat{a})) > \gamma$. This means that $J_{hh} > 1$.

APPENDIX F: PROOF OF PROPOSITION 5

The stability of the steady-state (a_2, h_2) is given by the roots of the characteristic polynomial $P(\lambda) = \lambda^2 - T\lambda + D = 0$, where $T = J_{hh} + J_{aa}$ and $D = J_{hh}J_{aa} - J_{ha}J_{ah}$ are the trace and the determinant of the Jacobian matrix obtained from the linearized system (34)–(35).

Using (36)–(39) and (25), we get:

$$\begin{aligned} T = {} & 1 + \gamma - \theta(\eta) + \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1} \\ & -(1-h)h\theta'(\eta)\left[\frac{\partial\eta}{\partial h} - \frac{a}{h}\frac{\partial\eta}{\partial a} + \frac{\partial\eta}{\partial a}\frac{\beta'(h)}{h(1+\beta(h))^2}((1-\tau^f)(1-s)Aa^s h + \tau)\right] \end{aligned} \tag{F1}$$

$$\begin{aligned} D = {} & \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1} \\ & \left[1 + \gamma - \theta(\eta) - (1-h)h\theta'(\eta)\left(\frac{\partial\eta}{\partial h} - \frac{a}{sh}\frac{\partial\eta}{\partial a}\right)\right] \end{aligned} \tag{F2}$$

We note that equation (25) with $h < 1$ implies that $\theta(\eta) > \gamma$. Using (A4), $\partial F/\partial a > 0$, $\theta'(\eta) < 0$, $\partial\eta/\partial h < 0$ and $\partial\eta/\partial a > 0$ at the steady-state (a_2, h_2), we deduce that $D < 1$.

Using (F1) and (F2), and also (25) and (26), we have:

$$\begin{aligned} P(1) = {} & 1 - T + D \\ = {} & (1-h)\left[1 - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\right]\left[\theta(\eta) + h\theta'(\eta)\frac{\partial\eta}{\partial h}\right] \\ & + (1-h)\frac{\theta'(\eta)}{h}\frac{\partial\eta}{\partial a}\left[b - \frac{\beta(h)}{1+\beta(h)}\tau + \frac{\beta'(h)h}{\beta(h)(1+\beta(h))}(ah+b)\right] \end{aligned} \tag{F3}$$

Substituting (A1) and (A2), $1 - T + D > 0$ is equivalent to $H_2'(a) > H_1'(a)$, where $H_2'(a)$ and $H_1'(a)$ are given by (C3) and (C4), respectively. This is satisfied for $\alpha > \underline{\alpha}$.

Using (25), (26), (A1), (A2), (F1), and (F2), we obtain:

$$\begin{aligned} P(-1) = {} & 1 + T + D \\ = {} & [2 - \theta(\eta)(1-h)]\left[1 + \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\right] \\ & + (1-h)\theta'(\eta)\left[(1-s)\frac{b-\tau}{\alpha Aha^s} + \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\frac{(1-s)b(1-\tau^f)}{\alpha ha}\right. \\ & \left. - s\frac{b(1-\tau^f)A - (b-\tau)a^{1-s}}{\alpha Aha^2}\frac{\beta'(h)}{\beta(h)(1+\beta(h))}(ah+b)\right] \end{aligned} \tag{F4}$$

Note that on the one hand, the second term (third line) on the right-hand side of this equation is negative because $\theta'(\eta) < 0$. On the other hand, the third term (fourth line) on the right-hand side of Equation (F4) is positive because $\theta'(\eta) < 0$ and $\partial\eta/\partial a > 0$. Moreover, using inequality (22), we note that $\theta(\eta)(1-h) < 1$. Since a_2 and h_2 have finite values, we easily deduce that there is $\widetilde{\beta}'(1) > 0$ such that $1 + T + D > 0$ and (a_2, h_2) is a sink for $(\beta'(h)>)\beta'(1) > \widetilde{\beta}'(1)$.

APPENDIX G: PROOF OF PROPOSITION 6

Under $\alpha > \underline{\alpha}$, inequality (40) and $b < b_2$, we have $F(\gamma/\theta(\tau^f/\alpha), \underline{a}\,) < 0$ or equivalently $H_2(\underline{a}\,) < H_1(\underline{a}\,)$ (see the proof of Proposition 2).

Since $\underline{h}\,\theta(\eta(\underline{h}, \hat{a}\,)) < \gamma$, the peak of $H_1(a)$ is above $\underline{h}$. We show now that it can be higher than $h = 1$. Indeed, $\widehat{h} = H_1(\hat{a}\,) > H_2(\hat{a}\,)(>1)$ is equivalent to:

$$F(\widehat{h}, \hat{a}\,) = \hat{a}\,\widehat{h}\left[1 - \frac{\beta(\widehat{h}\,)}{1 + \beta(\widehat{h}\,)}\frac{1 - s}{A}\frac{b - \tau}{b}\right] + b - \tau\frac{\beta(\widehat{h}\,)}{1 + \beta(\widehat{h}\,)} < 0 \tag{G1}$$

Under inequality (40), this is satisfied if $b(>\tau)$ is lower than an upper bound $b_2' > 0$. We note $b_b > 0$ as being $b_b \equiv \min\left\{b_2;\, b_2'\right\}$. Under $\alpha > \underline{\alpha}$, $H_2'(a) > H_1'(a)$ if $H_2(a) = H_1(a)$, which implies that $H_2(a)$ and $H_1(a)$ do not cross for all $a \in (\underline{a}, \hat{a}\,)$. Therefore, there are no steady-state with $h < 1$.

This also means that $H_1(a_1) > H_2(a_1) = 1$. This implies that $\theta(\eta(a_1, 1)) < \gamma$. Using the proof of Proposition 4, we deduce that the steady-state $(a_1, 1)$, which still exists, is stable.

APPENDIX H: PROOF OF PROPOSITION 7

Focusing on Equations (25) and (26) with $h < 1$, we have:

$$I\begin{pmatrix} da \\ dh \end{pmatrix} + \begin{pmatrix} \partial Z/\partial b \\ \partial F/\partial b \end{pmatrix} db = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

with

$$I = \begin{pmatrix} \partial Z/\partial a & \partial Z/\partial h \\ \partial F/\partial a & \partial F/\partial h \end{pmatrix}$$

Thus,

$$\begin{pmatrix} da \\ dh \end{pmatrix} = -I^{-1}\begin{pmatrix} \partial Z/\partial b \\ \partial F/\partial b \end{pmatrix} db$$

with

$$I^{-1} = \frac{1}{\mathrm{Det}\,I}\begin{pmatrix} \partial F/\partial h & -\partial Z/\partial h \\ -\partial F/\partial a & \partial Z/\partial a \end{pmatrix}$$

The endemic steady state outbreak (a_2, h_2) is characterized by $a_2 < \hat{a}$ and $H_2' = -\frac{\partial F / \partial a}{\partial F / \partial h} > H_1' = -\frac{\partial Z / \partial a}{\partial Z / \partial h}$. Using Lemma 1, at the point (a_2, h_2), we have $\partial Z/\partial a < 0$, $\partial Z/\partial h > 0$, $\partial F/\partial a > 0$ and $\partial F/\partial h < 0$. We thus deduce that $\text{Det}I < 0$.

The effect of a variation in debt on the endemic steady state outbreak (a_2, h_2) is given by:

$$\frac{da}{db} = -\frac{1}{\text{Det}I}\left(\frac{\partial F}{\partial h}\frac{\partial Z}{\partial b} - \frac{\partial Z}{\partial h}\right)$$

$$\frac{dh}{db} = -\frac{1}{\text{Det}I}\left(-\frac{\partial F}{\partial a}\frac{\partial Z}{\partial b} + \frac{\partial Z}{\partial a}\right)$$

with $-1/DetI > 0$.

We first examine the effect of a debt variation on h, examining the sign of dh/db. We have:

$$-\frac{\partial F}{\partial a}\frac{\partial Z}{\partial b} + \frac{\partial Z}{\partial a} = -h\left[1 - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\right]\theta'(\eta)\frac{a^{1-s} - (1-\tau^f)sA}{\alpha Aa} + \theta'(\eta)s\frac{b(1-\tau^f)A - (b-\tau)a^{1-s}}{\alpha Aa^2}$$

Thus, we have $dh/db > 0$ if and only if:

$$ah\left[1 - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\right](a^{1-s} - (1-\tau^f)sA) > sb(1-\tau^f)A - s(b-\tau)a^{1-s}$$

Since the left-hand side of this inequality is positive, there is $b_3 > 0$ such that it is satisfied if $b < b_3$.

We then examine the effect of a debt variation on the stationary capital-labor ratio, that is, da/db. Using the proof of Lemma 1, we have:

$$\frac{\partial F}{\partial h}\frac{\partial Z}{\partial b} - \frac{\partial Z}{\partial h} = -\theta'(\eta)\frac{\partial \eta}{\partial h}h - \theta(\eta(h,a)) + \theta'(\eta)\frac{\partial \eta}{\partial b}\left[\frac{\beta(h)}{1+\beta(h)}\tau - b - \frac{\beta'(h)h}{(1+\beta(h))^2}[(1-\tau^f)(1-s)Aa^s h + \tau]\right]$$

with, under Assumption 3:

$$\frac{\partial \eta}{\partial b} = \frac{a^{1-s} - (1-\tau^f)sA}{\alpha hAa} > 0; \ \frac{\partial \eta}{\partial h}h = \frac{b(1-\tau^f)sA - (b-\tau)a^{1-s}}{\alpha hAa} < 0$$

We thus have $-\frac{\partial \eta}{\partial h}h = \frac{\partial \eta}{\partial b}b - \frac{\tau a^{1-s}}{\alpha hAa}$

$$\frac{\partial F}{\partial h}\frac{\partial Z}{\partial b} - \frac{\partial Z}{\partial h} = \theta'(\eta)\left(\frac{\partial \eta}{\partial b}\left[\frac{\beta(h)}{1+\beta(h)}\tau - \frac{\beta'(h)h}{(1+\beta(h))^2}[(1-\tau^f)(1-s)Aa^s h + \tau]\right] - \frac{\tau a^{1-s}}{\alpha hAa}\right) - \theta(\eta(h,a))$$

$$\frac{\partial F}{\partial h}\frac{\partial Z}{\partial b} - \frac{\partial Z}{\partial h} = -\theta(\eta(h,a)) - \theta'(\eta)\frac{\tau a^{1-s} + (1-\tau^f)sA\tau\beta(h)}{\alpha Aha(1+\beta(h))} \\ -\theta'(\eta)\frac{a^{1-s} - (1-\tau^f)sA}{\alpha Aha}\frac{\beta'(h)h}{(1+\beta(h))^2}[(1-\tau^f)(1-s)Aa^sh + \tau] \tag{H1}$$

We have $da/db > 0$ if this last expression is strictly positive. $\frac{\partial F}{\partial h}\frac{\partial Z}{\partial b} - \frac{\partial Z}{\partial h} > 0$ is equivalent to:

$$\alpha Aa\gamma < -\theta'(\eta)\frac{\tau a^{1-s} + (1-\tau^f)sA\tau\beta(h)}{1+\beta(h)} - \theta'(\eta)[a^{1-s} - (1-\tau^f)sA]\frac{\beta'(h)h(ah+b)}{\beta(h)(1+\beta(h))} \tag{H2}$$

Therefore, there exist $\overline{\alpha} > 0$ and $\tilde{\alpha}(\geqslant\overline{\alpha})$ such that this inequality is satisfied for $\alpha < \overline{\alpha}$ and is not satisfied for $\alpha > \tilde{\alpha}$.[12]

$H_2'(a) > H_1'(a)$ is equivalent to $\alpha > \underline{\alpha}$, or (C5). Inequalities (H2) and (C5) are both satisfied for $\underline{\alpha} < \alpha < \overline{\alpha}$. This interval is nonempty if:

$$\frac{\beta'(h)h}{\beta(h)(1+\beta(h))}(ah+b)B_1 > B_2 \tag{H3}$$

with

$$B_1 \equiv a^{1-s} - (1-\tau^f)sA - s\frac{b(1-\tau^f)A - (b-\tau)a^{1-s}}{ah\partial F/\partial a} \tag{H4}$$

$$B_2 \equiv s\frac{b(1-\tau^f)A - (b-\tau)a^{1-s}}{ah\partial F/\partial a}\left(b - \frac{\beta(h)}{1+\beta(h)}\tau\right) - \frac{\tau a^{1-s} + (1-\tau^f)sA\tau\beta(h)}{1+\beta(h)} \\ -[(b-\tau)a^{1-s} - b(1-\tau^f)sA] \tag{H5}$$

Using $a > \underline{a}$, $B_1 > 0$ and $B_2 < 0$ if:

$$[(1-\tau^f)sA]^{\frac{1}{1-s}}h^2\frac{\tau}{b}\left(\frac{b}{b-\tau}\right)^{\frac{2-s}{1-s}}\left[1 - \frac{\beta(h)}{1+\beta(h)}(1-s)\frac{b-\tau}{b}\right] > b(1-s)$$

There exists $b_4 > 0$ such that this is satisfied if $b < b_4$.

APPENDIX I: PROOF OF PROPOSITION 8

The effect of a variation in τ^f on the endemic steady state outbreak (a_2, h_2) is given by:

$$I\begin{pmatrix} da \\ dh \end{pmatrix} + \begin{pmatrix} \partial Z/\partial\tau^f \\ \partial F/\partial\tau^f \end{pmatrix} d\tau^f = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

which implies that:

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[12] $\overline{\alpha}$ and $\tilde{\alpha}$ may not be equal because a, h and η depend on α.

$$\frac{da}{d\tau^f} = -\frac{1}{\mathrm{Det}I}\left(\frac{\partial F}{\partial h}\frac{\partial Z}{\partial \tau^f} - \frac{\partial Z}{\partial h}\frac{\partial F}{\partial \tau^f}\right)$$

$$\frac{dh}{d\tau^f} = -\frac{1}{\mathrm{Det}I}\left(-\frac{\partial F}{\partial a}\frac{\partial Z}{\partial \tau^f} + \frac{\partial Z}{\partial a}\frac{\partial F}{\partial \tau^f}\right)$$

with $-1/\mathrm{Det}I > 0$.

We first examine the effect of τ^f on h, examining the sign of $dh/d\tau^f$, which is given by the sign of:

$$-\frac{\partial F}{\partial a}\frac{\partial Z}{\partial \tau^f} + \frac{\partial Z}{\partial a}\frac{\partial F}{\partial \tau^f} = -h^2\left[1 - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\right]\theta'(\eta)\left(\frac{bs}{\alpha ha} + \frac{1}{\alpha}\right)$$
$$+ \theta'(\eta)s\frac{b(1-\tau^f)A-(b-\tau)a^{1-s}}{\alpha Aa^2}Aa^sh(1-s)\frac{\beta(h)}{1+\beta(h)}$$

Therefore, we have $dh/d\tau^f > 0$ if and only if:

$$\left[1 - \frac{\beta(h)}{1+\beta(h)}(1-\tau^f)(1-s)sAa^{s-1}\right]\left(\frac{bs}{a} + h\right) > s\frac{b(1-\tau^f)Aa^{s-1}-(b-\tau)}{a}(1-s)\frac{\beta(h)}{1+\beta(h)}$$

There exists an upper bound $b_5 > 0$ such that this inequality is satisfied for $b < b_5$.

We then examine the effect of a tax variation on the stationary capital stock, $da/d\tau^f$. It is given by the sign of the following expression:

$$\frac{\partial F}{\partial h}\frac{\partial Z}{\partial \tau^f} - \frac{\partial Z}{\partial h}\frac{\partial F}{\partial \tau^f} = h\theta'(\eta)\left(\frac{bs}{\alpha ha} + \frac{1}{\alpha}\right)\left[\frac{\beta(h)}{1+\beta(h)}\tau - b - \frac{\beta'(h)h}{(1+\beta(h))^2}[(1-\tau^f)(1-s)Aa^sh + \tau]\right]$$
$$-\left[\theta'(\eta)\frac{b(1-\tau^f)sA-(b-\tau)a^{1-s}}{\alpha hAa} + \theta(\eta)\right]Aa^sh(1-s)\frac{\beta(h)}{1+\beta(h)} \tag{I1}$$

This is positive if and only if:

$$-\frac{\theta'(\eta)}{1-s}\left(\frac{bs}{a^s} + ha^{1-s}\right)\left[\frac{1+\beta(h)}{\beta(h)}b - \tau + \frac{\beta'(h)h}{\beta(h)^2}(ah+b)\right]$$
$$-\theta'(\eta)[b(1-\tau^f)sA-(b-\tau)a^{1-s}] > \alpha\gamma Aa \tag{I2}$$

There exists $\overline{\alpha}_\tau > 0$ and $\widetilde{\alpha}_\tau (\geqslant \overline{\alpha}_\tau)$ such that this inequality is satisfied for $\alpha < \overline{\alpha}_\tau$ and is not satisfied for $\alpha > \widetilde{\alpha}_\tau$.[13]

$H_2'(a) > H_1'(a)$ is equivalent to $\alpha > \underline{\alpha}$, or (C5). Inequalities (H2) and (I2) are both satisfied for $\underline{\alpha} < \alpha < \overline{\alpha}_\tau$. This interval is nonempty if:

$$\left[\frac{\beta'(h)h}{(1+\beta(h))\beta(h)}(ah+b) + b - \frac{\beta(h)}{1+\beta(h)}\tau\right]$$
$$\left[\frac{1+\beta(h)}{\beta(h)}\left(\frac{bs}{(1-s)a^s} + \frac{ha^{1-s}}{1-s}\right) - s\frac{b(1-\tau^f)A-(b-\tau)a^{1-s}}{ah\partial F/\partial a}\right] > 0 \tag{I3}$$

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[13] $\overline{\alpha}_\tau$ and $\widetilde{\alpha}_\tau$ may not be equal because a, h, and η depend on α.

Since the first term into brackets is strictly positive, this inequality is satisfied if the second term into brackets is strictly positive. Using $a > \underline{a}$, this requires:

$$h^2 \frac{1+\beta(h)}{\beta(h)} \left(\frac{bs}{1-s} + \frac{h\underline{a}}{1-s} \right) \left[1 - \frac{\beta(h)}{1+\beta(h)} (1-s) \left(1 - \frac{\tau}{b} \right) \right] > (1-s)(b-\tau) \tag{I4}$$

Taking into account the expression of $\underline{a}$ given in Assumption 3, inequality (I4) is satisfied if τ is sufficiently close to b.

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Unequal Vulnerability to Climate Change and the Transmission of Adverse Effects Through International Trade

Karine Constant[1] · **Marion Davin**[2]

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Abstract
In this paper, we consider the unequal distribution of climate change damages in the world and we examine how the underlying costs can spread from a vulnerable to a non-vulnerable country through international trade. To focus on such indirect effects, we treat this topic in a North–South trade overlapping generations model in which the South is vulnerable to the damages entailed by global pollution while the North is not. We show that the impacts of climate change in the South can be sources of welfare loss for northern consumers in both the long and the short run. In the long run, an increase in the South's vulnerability can reduce the welfare in the North economy even in the case in which it improves the terms of trade of the North. In the short run, the South's vulnerability can also represent a source of intergenerational inequity in the North. Therefore, we emphasize the strong economic incentives for non-vulnerable—and a fortiori less vulnerable—economies to reduce the climate change damages on more vulnerable countries.

Keywords International trade · Climate change · Heterogeneous damages · Overlapping generations

JEL Classification F18 · F43 · O41 · Q56

1 Introduction

Climate change is one of the most serious environmental issues worldwide. While the substantial stock of greenhouse gases released into the atmosphere by human activities is responsible for global climate change, such change consists in return of an increase in

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✉ Marion Davin
marion.davin@umontpellier.fr

Karine Constant
karine.constant@u-pec.fr

[1] ERUDITE, UPEC, Université Paris Est, 61 Av.du Général de Gaulle, Mail des mèches, 94010 Créteil, France

[2] CEE-M, Univ. Montpellier, CNRS, INRA, Montpellier SupAgro, Montpellier, France

temperature and an increasing occurrence of extreme events, according to the Intergovernmental Panel on Climate Change (2014). A report by the United Nations Environment Program and the World Trade Organization reveals that the consequences from climate change are expected not only to become more widespread but also to intensify and that "even with small increases in average temperature, the type, frequency and intensity of extreme weather—such as hurricanes, typhoons, floods, droughts, and storms—are projected to increase" (WTO and UNEP 2009, p. viii). This global phenomenon therefore represents an increasing threat to economic activities that will lead to substantial losses in terms of production and population well-being, as well as a serious threat to intergenerational equity, by placing an increasing burden on future generations.

An interesting peculiarity of these losses is that their intensity varies considerably across countries. A large number of studies shows the higher vulnerability of developing countries to climate change (see e.g., Intergovernmental Panel on Climate Change 2014). The main reasons identified stem from their lower incomes, which limit their ability to adapt to weather changes, but also from geographical causes. Indeed, Stern (2006) points out that "climate change will have a disproportionately damaging impact on developing countries due, in part at least, to their location in low latitudes, the amount and variability of rainfall they receive, and the fact that they are 'already too hot' (see Mendelsohn et al. 2006)".

Some developed countries might accordingly be led to believe that the fight against climate change (i.e., mitigation) is mainly related to altruistic and fairness motives, and hence to behave as free riders and to focus on their own adaptation. However, even if they are relatively preserved from the direct consequences of global pollution, globalization and the resulting economic interdependence through international trade imply that damage from climate change in developing countries may also affect them. Empirically, Jones and Olken (2010) confirm that higher temperatures have no direct effect on rich countries' exports (at least for now), while they reduce significantly the growth of poor countries' exports. These authors conclude that rich regions may thus be indirectly affected by rising prices and decreasing quantities of goods imported from poor regions. Focusing on the agricultural sector, Costinot et al. (2016) also find that the ill effects of climate change are damped when production adjustments caused by the evolution of comparative advantage are taken into account. The macroeconomic consequences of climate change are therefore related to its effects on trade flows, on comparative advantage across countries and, more generally, on international trade. All these elements hence stress the importance of studying if and how pollution costs could be transmitted from developing to developed countries through international trade. This is the purpose of our paper.

Overall, there is an extensive literature on trade and the environment, much of which attempts to explain the specialization of countries in green or polluting activities (see Copeland and Taylor 2004 for a literature review). In particular, trade theory identifies the role of differences in the stringency of environmental regulation (pollution haven hypothesis), in factor endowments or in technology between countries to explain trade flows. However, to date, little attention has been paid to the disparities of countries in terms of vulnerability to environmental damage while such vulnerability could have significant consequences for international trade.

In this regard, two recent contributions represent notable exceptions. On the one hand, using a computable general equilibrium model, Schenker (2013) shows that exogenous damage to developing countries affects the relative prices of goods and in this way deteriorates the terms of trade of developed countries. He estimates that such an effect could be responsible for 16.4% of the total expected cost of climate change in the United States in

2100. On the other hand, through a static general equilibrium model, Ollivier (2016) points out that northern countries can have comparative advantage in the dirty sector, due to the lower vulnerability of their consumers to pollution that leads to less stringent environmental regulation. Moreover, she finds that this specialization pattern benefits the welfare of northern agents.[1]

Consequently, while it is clear that the higher vulnerability to climate change of developing countries may affect the national welfare of developed countries through international trade, determining whether this effect is positive or negative and identifying the mechanisms through which it occurs remain open and crucial issues. This paper aims to shed some new light on these questions. For that, we consider the possible changes in both the terms of trade and the comparative advantage of countries over time, therefore extending the works of Schenker (2013) and Ollivier (2016).

In addition, we go one step further by taking into account the intergenerational dimension of the consequences associated with the unequal vulnerability of countries to climate change. The reason is twofold. First, considering that generations overlap, agents may over- or under-accumulate capital relative to the Pareto optimum. The potential impact of damage on the behavior of agents may thus have different economic implications according to the dynamic efficiency properties of the economy.

Second, the welfare effects of the unequal damage may also be unequally distributed across generations. Such welfare variations across generations correspond to intergenerational inequity. Since Howarth and Norgaard (1992) and John and Pecchenino (1994), authors have increasingly explored this dimension in environmental economics and emphasized that pollution may indeed lead to intergenerational inequity (see e.g., Seegmuller and Verchère 2004; Schumacher and Zou 2008; Varvarigos 2011; Constant and Davin 2019). Given the high persistence of greenhouse gases in the atmosphere, such a key issue seems particularly important in the context of climate change.

To deal with all these dimensions, we are using a dynamic general equilibrium model with overlapping generations. We formalize two regions, North and South, representing developed and developing countries respectively. They can produce and trade two goods—a green good and a brown good whose production generates pollution emissions. The stock of pollution, which evolves over time with economic activity, is responsible for damages unequally distributed around the world. There is a risk—increasing with the pollution stock—that extreme events destroy a share of the production. In this paper, we do not examine the uncertainty associated with extreme weather but focus on the deterministic effect of pollution on economic activity. Therefore, our pollution damages can also represent the productivity loss associated with the increase in temperature (see e.g., Dell et al. 2012; Burke et al. 2015). To take into account the significant difference in terms of vulnerability between countries in a simple way, we assume that South is the only region that suffers from the direct damages due to climate change, while North is non-vulnerable.

With this dynamic model, we determine that the lifetime welfare of northern agents evolves across time until the economy converges to its long-term state. When the South' production is altered by climate change, the usual positive trend in welfare resulting from capital accumulation is questioned for both countries. More precisely, in the South region, climate damages negatively impact the net output of firms, and hence the remuneration of

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[1] However, note that the issues addressed by Ollivier (2016) differ from ours. While we focus on the transmission of indirect effects of climate change across countries, she examines whether trade increases pollution and/or welfare given the unequal vulnerability of countries to pollution.

production factors and capital accumulation. By making capital scarcer, pollution affects world prices and entails a negative income effect on northern agents. When pollution becomes too high, so does the extent of this negative effect. Therefore, we can observe that the welfare of successive northern generations declines constantly over time, characterizing intergenerational inequity as the younger generation is worse off than its parents.

Second, in the long run, we examine how an increase in the vulnerability of the South to climate change affects the stationary welfare of northern agents. We identify two channels: a terms of trade effect and a dynamic (in)efficiency effect. Both effects occur through the decrease in the world relative price of the green good driven by the increase in damages.

On the one hand, movements in the world price modify the terms of trade. This change generates a positive or a negative impact on welfare in the North depending on its comparative advantage, which itself depends on the extent of the South's vulnerability. When this vulnerability is low, the North has a comparative advantage in the green sector. However, when this vulnerability is high, the relative capital abundance of the North becomes sufficiently high that it has a comparative advantage in the polluting—capital intensive—activities, despite its larger productivity in the green production. While the fall in the relative price of green to brown goods deteriorates the terms of trade of the North in the first case, it improves the terms of trade when the North is a net exporter of the polluting good. Thus, the terms of trade effect on northern agents' welfare is positive when the South's vulnerability is high, and negative otherwise.

On the other hand, the dynamic (in)efficiency effect depends on the dynamic efficiency properties of the North; i.e., if northern agents under- or over-accumulate capital with respect to the socially optimal solution. As the vulnerability of the South decreases the relative price of the green—labor intensive—good, damages entail a negative income effect on northern workers which reduces their ability to accumulate capital. Therefore, this effect is positive on welfare when the North over-accumulates capital, while otherwise, it worsens under-accumulation and harms the welfare of agents.

The two effects of the South's vulnerability to climate change on northern agents' welfare can act either in the same or opposite directions. In the end, we show that the North region suffers from the higher damages abroad, as long as agents' preferences for present over future consumption are sufficiently high. Unlike Schenker (2013), we obtain this outcome even if there is an improvement in the North's terms of trade. Most importantly, we find that for realistic calibrations of the model, the North is always affected negatively in the long run by the damages from climate change in the South, even if the North is not directly vulnerable to it. Our results identify therefore strong incentives for developed countries to reduce the climate change damages on developing countries.

The paper is organized as follows. In Sect. 2, we introduce the theoretical model. Section 3 focuses on the equilibrium in the world economy with free trade, while the welfare implications of environmental damages are examined in Sect. 4. Finally, we conclude and discuss the policy implications of our results in Sect. 5, while technical details are relegated to an "Appendix".

2 The Model

Consider an infinite-horizon world economy comprising finitely-lived individuals and perfectly competitive firms. Time is discrete and indexed by $t = 0, 1, 2, \ldots, \infty$. The world economy consists of two large (industrialized) regions, North and South, referred to N and

S, respectively. We assume a dynamic Ricardian framework in which the two regions differ only with respect to their total factor productivity (TFP) in each sector and their vulnerability to climate change. They are identical in terms of labor endowment, technologies and preferences.

2.1 Production and Pollution

In each competitive economy $i \in \{N, S\}$, there are two sectors $j \in \{b, g\}$ with one representative firm per sector and each firm produces one tradable good by using capital and labor resources at each date. The two goods consist of a brown good $Y^i_{b,t}$ and a green good $Y^i_{g,t}$. For simplicity, the brown good production generates a pollution flow, while the green good production does not. The stock of labor is normalized to one and given by $L^i_t = L^i_{b,t} + L^i_{g,t} = 1$, and the capital stock is given by $K^i_t = K^i_{b,t} + K^i_{g,t}$. Using these production factors, the two goods are assumed to be produced with a Cobb–Douglas technology in each region:

$$Y^i_{j,t} = A^i_j (K^i_{j,t})^{\alpha_j} (L^i_{j,t})^{1-\alpha_j}, \tag{1}$$

where $0 < \alpha_j < 1$ is the distribution parameter for factors in sector j and A^i_j is the total factor productivity (TFP) in sector j. In this paper, we consider the cross-region differences in sectoral TFP A^i_j as a motive for international trade, in accordance with recent empirical contributions (e.g., Fadinger and Fleiss 2011; Kerr 2018).[2]

Regarding the pollution intensity of sectors, it is found empirically that more physical capital intensive sectors generate more pollution than those relying more heavily on labor, in both developing and developed economies, partly because of their larger consumption in terms of energy (see e.g., Cole and Elliott 2005; Cole et al. 2008; Managi et al. 2009; Broner et al. 2012). A recent study by Andersen (2017) also concludes that pollution emission is higher for industries that use more intensively tangible assets, such as physical capital, than intangible assets, such as human capital. We therefore assume that the brown sector is more physical capital intensive and produces an investment good (i.e., capital good), while the green sector produces a consumption good. The brown good is therefore fully saved and invested to accumulate physical capital. It provides new units of physical capital (e.g., machinery, tools, buildings…).[3]

Assumption 1 $\alpha_b > \alpha_g$.

The flow of pollution emissions in each region i is a by-product of its production of the brown good $Y_{b,t}$.

$$E^i_t = \theta Y^i_{b,t}, \tag{2}$$

with $\theta > 0$ an exogenous parameter, identical in each region, that controls the size of the carbon intensity.

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[2] The paper does not deal with environmental regulation and hence leaves aside the *Pollution Haven Hypothesis* issue.

[3] We could consider the case where the brown sector produces a composite good used to save and to consume. However, it would make the analysis much more complex without changing the results (as long as the elasticity of substitution between brown and green consumption goods is one).

The global stock of pollution, representing the stock of greenhouse gases (hereafter GHG, e.g., carbon dioxide, methane, nitrous oxide or ozone) in the atmosphere, increases with the emission flows of each region and partly leaves the atmosphere through a natural process in a share $0 < \eta < 1$ (finite lifetime of GHG).

$$G_{t+1} = (1-\eta)G_t + E_t^N + E_t^S. \tag{3}$$

As in Golosov et al. (2014) and Dietz and Stern (2015), we consider that damages due to the level of GHG reduce the aggregate output. More precisely, at each period, the stock of pollution causes a damage that destroys a part $1-\Psi^i(G_t)$ of production in each sector. We define the undamaged part of production $\Psi^i(G_t)$ as this standard functional form:

$$\Psi^i(G_t) = \frac{1}{1+\gamma^i G_t^2}, \tag{4}$$

where $\gamma^i > 0$ captures the vulnerability of region i to global pollution. Damages are hence maximum (i.e., all production is destroyed) when G_t tends to $+\infty$ ($\Psi^i(G_t) \to 0$), while they are minimum (i.e., production is not affected) when G_t tends to 0 ($\Psi^i(G_t) \to 1$).

This paper takes into account the fact that developing countries are much more vulnerable to climate change than developed countries (see e.g., Mendelsohn et al. 2006; Stern 2006; Intergovernmental Panel on Climate Change 2014). To represent this significant difference in terms of vulnerability in a simple way and to focus on how climate change may affect the North through trade, we assume that the South is the only region that suffers from climate change, and thus that there is no direct damage in the North (i.e., $\gamma^N = 0$). Then, in the remainder of the paper, we assume the following.[4]

Assumption 2 $\gamma^N = 0$ and $\gamma^S = \gamma > 0$.

In region i, the representative firm of each sector j chooses inputs by maximizing its profit Π_j^i at each period t. Assuming perfect factor mobility between sectors, the latter are given by the following equation.

$$\Pi_{j,t}^i = p_{j,t}^i \Psi^i(G_t) Y_{j,t}^i - R_t^i K_{j,t}^i - w_t^i L_{j,t}^i, \tag{5}$$

where $p_{j,t}^i$ denotes the price of good j in region i and w_t^i and R_t^i denote the wage and the rental rate of physical capital in region i, respectively. With competitive factor markets, workers and capital owners are paid their marginal value products by the industry in which they are employed. With $k_{j,t}^i \equiv K_{j,t}^i / L_{j,t}^i$ representing the physical capital intensity of sector j, we derive the following factor prices.

$$R_t^i = \Psi^i(G_t) A_j^i \alpha_j (k_{j,t}^i)^{\alpha_j - 1} p_{j,t}^i; \quad w_t^i = \Psi^i(G_t) A_j^i (1-\alpha_j)(k_{j,t}^i)^{\alpha_j} p_{j,t}^i. \tag{6}$$

We let the brown good be the numeraire and normalize its price to 1 such that $p_{g,t}^i$ is the price of the green good as well as the relative price of green to brown goods. Solving the first-order conditions (6) with perfect mobility of factors between sectors, we obtain the optimal demand function for the physical capital intensity used in each sector.

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[4] We could consider the case where $0 < \gamma^N < \gamma^S$ but it would make the analysis much more complex without qualitatively changing the results.

$$\frac{k^i_{g,t}}{k^i_{b,t}} = \frac{(1-\alpha_b)\alpha_g}{(1-\alpha_g)\alpha_b}. \tag{7}$$

Then, we deduce from the two previous equations that the relative price of the green good $p^i_{g,t}$ is:

$$p^i_{g,t} = \left(\frac{A^i_b}{A^i_g}\right)\left(\frac{k^i_{b,t}}{\Lambda_b}\right)^{\alpha_b-\alpha_g}, \tag{8}$$

with

$$\Lambda_b = \left(\frac{\alpha_g}{\alpha_b}\right)^{\frac{\alpha_g}{\alpha_b-\alpha_g}}\left(\frac{1-\alpha_g}{1-\alpha_b}\right)^{\frac{1-\alpha_g}{\alpha_b-\alpha_g}}.$$

By combining Eq. (6) with (8), factor returns can be expressed as follows:

$$\begin{aligned} R^i_t &= \Psi^i(G_t)A^i_b\alpha_b\Lambda_b^{\alpha_b-1}\left(\frac{A^i_g}{A^i_b}\right)^{\frac{\alpha_b-1}{\alpha_b-\alpha_g}}\left(p^i_{g,t}\right)^{\frac{\alpha_g-1}{\alpha_b-\alpha_g}}; \\ w^i_t &= \Psi^i(G_t)A^i_b(1-\alpha_b)\Lambda_b^{\alpha_b}\left(\frac{A^i_g}{A^i_b}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}}\left(p^i_{g,t}\right)^{\frac{\alpha_g}{\alpha_b-\alpha_g}}. \end{aligned} \tag{9}$$

We easily identify the Stolper–Samuelson theorem such that when the relative price of the good g decreases, the return of the factor intensively used to produce this good decreases, while the return of the other factors increases. Therefore, under Assumption 1, the relative price of the green good has a negative effect on capital return and a positive effect on wages.

Using Eq. (7) and the full-employment conditions for factors, i.e., $K^i_t = k^i_{b,t}L^i_{b,t} + k^i_{g,t}L^i_{g,t}$, we can express the labor used in the green sector $L^i_{g,t}$ and in the brown sector $L^i_{b,t}$ as:

$$L^i_{g,t} = \frac{\left(1-\alpha_g\right)\alpha_b\left(k^i_{b,t}-K^i_t\right)}{k^i_{b,t}(\alpha_b-\alpha_g)}, \quad L^i_{b,t} = \frac{\alpha_b(1-\alpha_g)K^i_t - k^i_{b,t}\alpha_g(1-\alpha_b)}{k^i_{b,t}(\alpha_b-\alpha_g)}. \tag{10}$$

2.2 Households

We consider an overlapping generations economy. At each date t, a new generation of identical agents is born. We assume no population growth and we normalize to 1 the population size of each generation. Households in each region live for two periods—youth and old age. A representative agent born in period t cares about her/his consumption when young and old (c^i_t and d^i_{t+1}, respectively). Her/his preferences are described by the following utility function:

$$U\left(c^i_t, d^i_{t+1}\right) = \ln c^i_t + \beta \ln d^i_{t+1}, \tag{11}$$

where $\beta \in (0, 1]$ denotes the individual preference rate for the future.

When young, the agent inelastically supplies one unit of labor remunerated at wage w_t^i. She/he allocates her/his income to consumption c_t^i and to savings s_t^i. When old, she/he is retired and uses the entire return on her/his savings $R_{t+1}^i s_t^i$ to consume d_{t+1}^i. Therefore, the representative agent solves the following dynamic program:

$$\max_{c_t^i, d_{t+1}^i, s_t^i} \left\{ \ln c_t^i + \beta \ln d_{t+1}^i \mid p_{g,t}^i c_t^i + s_t^i = w_t^i,\ p_{g,t+1}^i d_{t+1}^i = s_t^i R_{t+1}^i \right\}. \tag{12}$$

Solving the first-order conditions gives the standard agent's optimal choices:

$$s_t^i = \frac{\beta}{1+\beta} w_t^i, \quad p_{g,t}^i c_t^i = \frac{1}{1+\beta} w_t^i, \quad p_{g,t+1}^i d_{t+1}^i = \frac{\beta}{1+\beta} R_{t+1}^i w_t^i. \tag{13}$$

3 Free Trade Equilibrium

The world economy is composed of two regions, in which there is free trade in the brown and the green goods, while production factors (labor and capital) are immobile across regions. In other words, we assume that new units of capital are tradable, as the good used to invest in physical capital is free to move, but that the existing stock of capital is not.[5]

The two regions differ in terms of sectoral TFP and of vulnerability to climate change damages.[6] As the size of countries acts only as a scale effect in this paper, we assume that North and South have the same size.

Under free trade in the output of the green and the brown sectors, the relative price of the green good in terms of the brown good at each t is common to both regions and denoted $p_{g,t}^W$. Following Assumption 2, we denote for the rest of the analysis $\Psi^N = 1$ and $\Psi^S = \Psi$.

3.1 Intertemporal Equilibrium

We define an intertemporal diversified equilibrium.

Definition 1 Given the initial conditions $K_{t=0}^i$ and $G_{t=0}$,[7] a perfect-foresight diversified competitive equilibrium is the sequence $\left\{K_t^i, G_t\right\}_{t=0}^{\infty}$ such that, for all $t \geqslant 0$:

(i) Factor prices are given by (6) and are identical in both sectors;
(ii) Households are at their optimum: The first-order conditions given by (13) are satisfied;
(iii) The market clearing condition for the brown good is given by $Y_{b,t}^N + \Psi(G_t) Y_{b,t}^S = s_t^N + s_t^S$;

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[5] Following Yenokyan et al. (2014), this assumption means that once the investment has been put in place, the resulting stock is not mobile. Note that this is the standard specification in the dynamic trade model with two tradable goods, since Oniki and Uzawa (1965).

[6] Assuming that countries differ in time preferences, β, would affect the relative capital scarcity of countries but would not change our results qualitatively.

[7] The initial conditions on $K_{t=0}^i$ and $G_{t=0}$ imply that $p_{g,t=0}^W$ is given.

(iv) The physical capital accumulation equation is given by $K^i_{t+1} = s^i_t$;[8]
(v) Equation (2) gives the equilibrium value of the pollution flow;
(vi) The equilibrium is diversified in each region $L^i_{j,t} \in (0, 1)$.

From Definition 1, we have that the trade balance condition is satisfied. Without international lending or borrowing, the net export of the brown good in the North, $Y^N_{b,t} - s^N_t$, is equal to its net import of the green good, $p^w_{g,t}\left(-Y^N_{g,t} + c^N_t + d^N_t\right)$. The same condition holds for the South.

From the production functions defined in (1) and the optimal choices of consumers (13), the equilibrium condition on the brown good market [(iii) in Definition 1] can be rewritten as:

$$A^N_b L^N_{b,t}\left(k^N_{b,t}\right)^{\alpha_b} + A^S_b L^S_{b,t}\left(k^S_{b,t}\right)^{\alpha_b}\Psi(G_t) = \frac{\beta}{1+\beta}\left(w^N_t + w^S_t\right). \tag{14}$$

From (6) and (8), it follows that the behavior of the two trading economies over time is determined by the evolution of the world relative price $p^W_{g,t}$ and of the global stock of GHG G_t, both common to the two regions.

Lemma 1 *The dynamics of the world diversified economy is driven by the following equations*:

$$\left(\frac{(p^W_{g,t})^{\alpha_b}}{p^W_{g,t+1}}\right)^{\frac{1}{\alpha_b-\alpha_g}} = \frac{\frac{\beta\alpha_b+\alpha_g}{\beta\alpha_b(1-\alpha_g)}\left(1+(B)^{\frac{\alpha_g}{\alpha_b-\alpha_g}}\left(\frac{1}{T}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}}\Psi(G_t)\right)}{x\left(1+\left(\frac{1}{B}\right)^{\frac{1-2\alpha_g}{\alpha_b-\alpha_g}}(T)^{\frac{1-2\alpha_b}{\alpha_b-\alpha_g}}\Psi(G_t)^2\right)}, \tag{15}$$

$$\begin{aligned} G_{t+1} &= (1-\eta)G_t + \left(A^N_b\right)^{\frac{1}{1-\alpha_b}}(p^W_{g,t})^{\frac{\alpha_b}{\alpha_b-\alpha_g}} x^{\frac{\alpha_b}{\alpha_b-1}}\theta L^N_{b,t} \\ &\quad + \Lambda^{\alpha_b}_b (p^W_{g,t})^{\frac{\alpha_b}{\alpha_b-\alpha_g}} A^S_b\left(\frac{A^S_g}{A^S_b}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}}\theta L^S_{b,t}, \end{aligned} \tag{16}$$

with $T \equiv \frac{A^N_g}{A^S_g}$, $B \equiv \frac{A^N_b}{A^S_b}$, $x \equiv A^N_b\left(\frac{A^N_b}{A^N_g}\right)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}}\Lambda^{\alpha_b-1}_b$ *and*

---

[8] Capital depreciates fully in one period (equivalent to 40 years) such that the stock in $t+1$ is given only by the amount of savings in t. By combining (iii) and (iv), the capital stock in $t+1$ corresponds thus to the brown good production in both countries: $Y^N_{b,t} + \Psi(G_t)Y^S_{b,t} = K^N_{t+1} + K^S_{t+1}$.

$$
\begin{aligned}
L^N_{b,t+1} &= \frac{(1-\alpha_b)}{(\alpha_b-\alpha_g)}\left[-\alpha_g + \frac{\alpha_b\beta}{1+\beta}(1-\alpha_g)x\left(\frac{\left(p^W_{g,t}\right)^{\alpha_b}}{p^W_{g,t+1}}\right)^{\frac{1}{\alpha_b-\alpha_g}}\right] \equiv L^N_b(T,G_t),\\
L^S_{b,t+1} &= \frac{(1-\alpha_b)}{(\alpha_b-\alpha_g)}\left[-\alpha_g + \frac{\alpha_b\beta}{1+\beta}(1-\alpha_g)x\left(\frac{T^{1-\alpha_b}}{B^{1-\alpha_g}}\right)^{\frac{1}{\alpha_b-\alpha_g}}\left(\frac{\left(p^W_{g,t}\right)^{\alpha_b}}{p^W_{g,t+1}}\right)^{\frac{1}{\alpha_b-\alpha_g}}\Psi(G_t)\right]\\
&\equiv L^S_b(T,G_t),
\end{aligned}
\tag{17}
$$

where $\partial L^N_b/\partial T < 0$ *and* $\partial L^S_b/\partial T > 0$. *Moreover, we have that* $\partial L^S_b/\partial G_t < 0$ *and* $\partial L^N_b/\partial G_t > 0$ *when* $0 < L^S_b(T,G_t), L^N_b(T,G_t) < 1$, *and that* $\lim_{G_t\to\infty} L^S_b(T,G_t) < 0$ *and* $\lim_{G_t\to\infty} L^N_b(T,G_t) > 0$.

Proof See "Appendix 1". □

In this model, trade results from two forces. The first is the standard Ricardian force, such that a region has a comparative advantage in the sector in which it is relatively more productive. The second force emerges from the relative "endowments" of the production factors. While countries are assumed to have the same exogenous labor endowment $L^N = L^S = 1$, physical capital is produced and accumulated over time according to the country's TFP and its vulnerability to climate change. The two regions thus differ in their capital stock for all $t > 0$, even if they start with the same capital endowment.

Figure 1 illustrates how global pollution impacts the capital stock in the South. Pollution leads to damages in the South economy, meaning that the net outputs of the southern firms in both sectors decrease. Thus, their profits and the remuneration of the factors they use are affected negatively. As damages from climate change reduce the wages of southern workers, they also diminish the ability to save and the stock of capital in the South. In this way, the level of global pollution modifies the relative capital abundance between countries and the world relative price of goods.[9]

Without loss of generality, we restrict our analysis to the most realistic trade pattern; i.e., one in which production is diversified in both regions and the North is a net exporter of the green production when there is no climate change damage. For this purpose and from Lemma 1, we shall assume the following.

Assumption 3 Using (17), we define T^i_1 and T^i_2 as $L^i_b(T^i_1, 0) = 0$ and $L^i_b(T^i_2, 0) = 1$. We assume $T \in (\underline{T}, \overline{T})$ with $\underline{T} = B^{\frac{1-\alpha_g}{1-\alpha_b}}$ and $\overline{T} = \min\{T^S_2, T^N_1\}$.

This assumption has two main implications. First, $T > \underline{T}$ ensures that in the absence of damage, a country relatively more productive in the green sector is a net exporter of this good; i.e., the Ricardian law of comparative advantage holds.[10] A condition is

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[9] The mechanisms linking the world relative price p^W_g to pollution are further detailed in Sect. 4.1.

[10] This condition implies $L^S_b(T,0) > L^N_b(T,0)$.

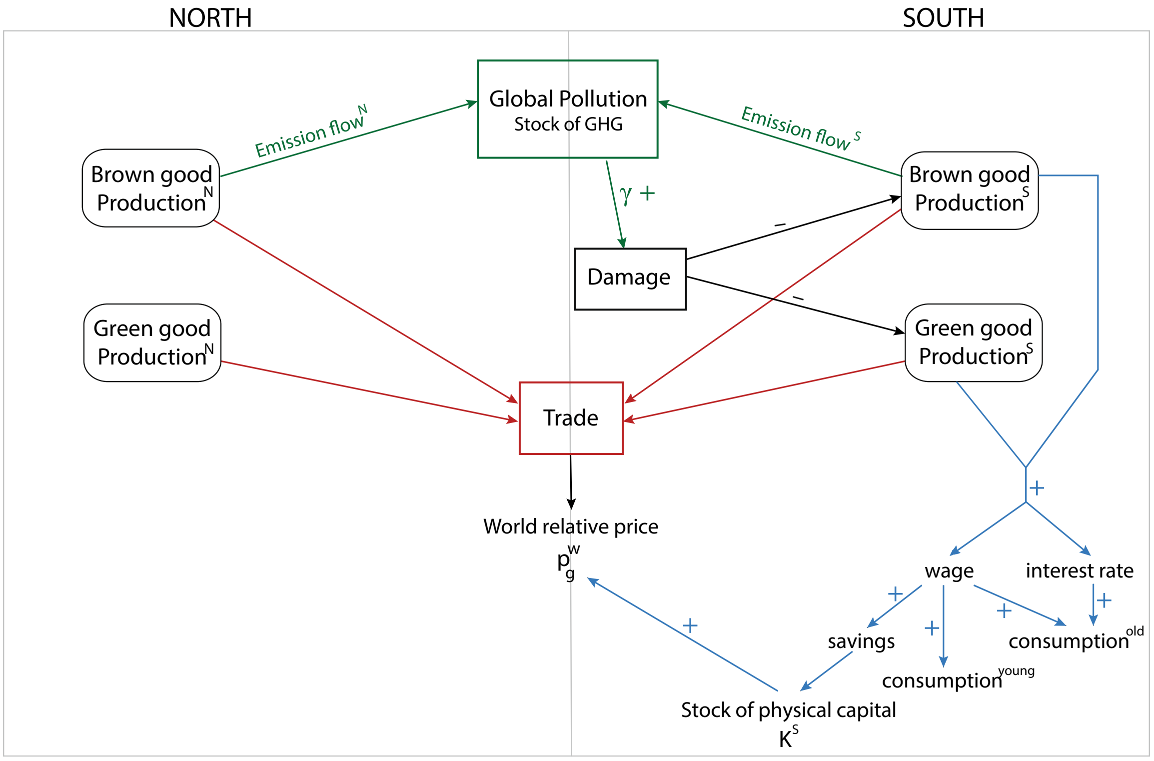

Fig. 1 Structure of the model

required to satisfy this law because when the North is more productive in both sectors with a comparative advantage in the green one, it accumulates more capital than the South and therefore has an incentive to specialize in the capital intensive (brown) production. Thus, in order to ensure a comparative advantage of the North in green industries, capital intensity differences between the brown and the green sector must not be too large ($\alpha_b - \alpha_g$ low) with respect to the relative TFP advantage in the green sector for the North (T/B large).

Second, $T < \bar{T}$ means that cross-country TFP differences are not too large so that both countries produce both goods in the absence of damage.

In the presence of damages from climate change, there is an additional condition on the level of pollution so that production remains diversified; i.e., the labor of each country is used in both sectors $L_j^i \in (0, 1)$. For this purpose, using Lemma 1, we define G_1 and G_2 two levels of pollution such that $L_b^S(T, G_1) = 0$ and $L_b^N(T, G_2) = 1$ and consider the case in which:

$$G_t < \Omega; \text{with} \quad \Omega = \min\{G_1, G_2\}. \tag{18}$$

We focus our attention on the simplest and the most relevant case, i.e., diversified production in both countries with and without damages. However, this condition on pollution does not imply that the North always has a comparative advantage in the green production. As pollution evolves across time, so can comparative advantages. Thus, we do not restrict our analysis to one configuration of comparative advantage or the other; i.e, the North and the South can have a comparative advantage in green or brown production.

3.2 Steady State

At the steady state, the stock variables achieve a stationary level and the world relative price of the green good is constant. Denoting the steady state levels of pollution and world relative price as $\bar{G}$ and $\bar{p}_g^W$, respectively, we obtain from Lemma 1:

Lemma 2 *Under Assumptions 1–3, the steady state of the world economy is characterized by the following set of equations*:

$$\bar{p}_g^W = \left(\bar{G}\right)^{\frac{\alpha_b-\alpha_g}{\alpha_b}} \left(\frac{\theta}{\eta}\frac{(1-\alpha_b)}{(\alpha_b-\alpha_g)}(A_b^N)^{\frac{1}{1-\alpha_b}}\right)^{\frac{-\alpha_b+\alpha_g}{\alpha_b}} \times \left(\frac{(\beta\alpha_b+\alpha_g)\Upsilon(\bar{G})}{(1+\beta)}\left[1+\Psi(\bar{G})\left(\frac{B}{T}\right)^{\frac{1}{\alpha_b-\alpha_g}}\right] - \alpha_g\left[1+\left(\frac{B^{\alpha_g}}{T^{\alpha_b}}\right)^{\frac{1}{\alpha_b-\alpha_g}}\right]\right)^{\frac{-\alpha_b+\alpha_g}{\alpha_b}}, \tag{19}$$

$$\bar{p}_g^W = \left(\frac{\beta\alpha_b+\alpha_g}{x\beta\alpha_b(1-\alpha_g)}\Upsilon(\bar{G})\right)^{\frac{\alpha_b-\alpha_g}{\alpha_b-1}}, \tag{20}$$

$$\bar{G} < \Omega, \tag{21}$$

with

$$\Upsilon(\bar{G}) = \frac{1+\Psi(\bar{G})\left(\frac{B^{\alpha_g}}{T^{\alpha_b}}\right)^{\frac{1}{\alpha_b-\alpha_g}}}{1+(\Psi(\bar{G}))^2\left(\frac{1}{B}\right)^{\frac{1-2\alpha_g}{\alpha_b-\alpha_g}}(T)^{\frac{1-2\alpha_b}{\alpha_b-\alpha_g}}}. \tag{22}$$

From this lemma, we study the existence and the unicity of a steady state equilibrium and derive the following result:

Proposition 1 *Let $\bar{G} \equiv G(\gamma)$ and $\Omega \equiv \Omega(\gamma)$. Under Assumptions 1–3, there exists a threshold $\bar{\gamma}$ such that $G(\bar{\gamma}) = \Omega(\bar{\gamma})$. If the condition $\gamma < \bar{\gamma}$ holds, the world economy achieves a stable steady state equilibrium in which both economies are diversified.*

Proof See "Appendix 2" □

The condition in terms of pollution such that production is diversified in both countries ($G_t < \Omega$) can be rewritten at the steady state as a condition on the South's vulnerability ($\gamma < \bar{\gamma}$). Indeed, the vulnerability of the South to climate change must not be too high to guarantee that both economies are still producing both goods at the steady state in the presence of pollution. Conversely, if this condition does not hold, extreme cases with perfect specialization of either one or both of these countries or with permanent fluctuations between the different patterns of specialization (complete and incomplete in either good) may emerge. In these extreme cases such as the case considered in this proposition ($\gamma < \bar{\gamma}$), the range of vulnerability includes values that allow countries' comparative advantages change due to damages. However, the analysis is much more tractable and realistic in the latter case. Therefore, we consider the South's vulnerability γ included in the interval $(0, \bar{\gamma})$ throughout the paper, in order to focus on the possible transmission of climate change effects through trade.

4 Welfare Analysis

This section explores how the welfare of consumers in a country that is not directly vulnerable to climate change, i.e., the North, could be affected by the climate damages occurring in other countries, i.e., the South. Such a welfare analysis enables us to examine carefully the indirect effects of climate change on developed countries that occur through international trade, in addition to its existing direct consequences.

In an international trade context, an event occurring in one country is felt by all regions of the trading area once the event modifies prices on international market. As a result, damage that destroys a part of the production in the South affects its trading partners through the modification of the world relative price p_g^W it entails. The welfare in the North economy therefore evolves with the global stock of pollution. In the following sections, we examine the implications of pollution for the lifetime utility of a representative northern consumer in both the short and the long run.

4.1 Short-Run Implications

In this section, we consider how the welfare of successive northern generations evolves over time when the South is vulnerable to climate change.

Using the demand functions given by (13) and expressing factor prices with (9), the northern agents' welfare—indirect utility—is given by the following function:

$$V^N(p_{g,t}^W, p_{g,t+1}^W) = C_1 + \left(\frac{\alpha_g + \alpha_b \beta}{\alpha_b - \alpha_g}\right) \ln\left(p_{g,t}^W\right) - \beta\left(\frac{1-\alpha_g}{\alpha_b - \alpha_g}\right) \ln\left(p_{g,t+1}^W\right), \tag{23}$$

with C_1 a constant whose value is given in "Appendix 3".

From Eq. (23), we see that the lifetime income of an agent born at time t depends positively on the world relative price of good g at time t and negatively on the world relative price of good g at time $t+1$. This effect occurs because income during the working period is driven by the return of labor at time t, which increases with $p_{g,t}^W$, while income during the retirement period depends on the return of capital at time $t+1$, which decreases with $p_{g,t+1}^W$. Using Eq. (15), we can define the relative price at time $t+1$ as a decreasing function of the pollution stock at time t because the latter reduces the stock of capital at time $t+1$. Indeed, as summarized in Fig. 1, the global pollution G_t entails damages that negatively affect the current net output of southern firms and hence the wages they pay to workers w_t^S. In this way, southern workers' savings s_t^S and the resulting capital stock in this region K_{t+1}^S fall. As capital becomes scarcer in the South, the world relative price of the capital intensive good b increases, meaning that the world relative price of the green good $p_{g,t+1}^W$ decreases. This

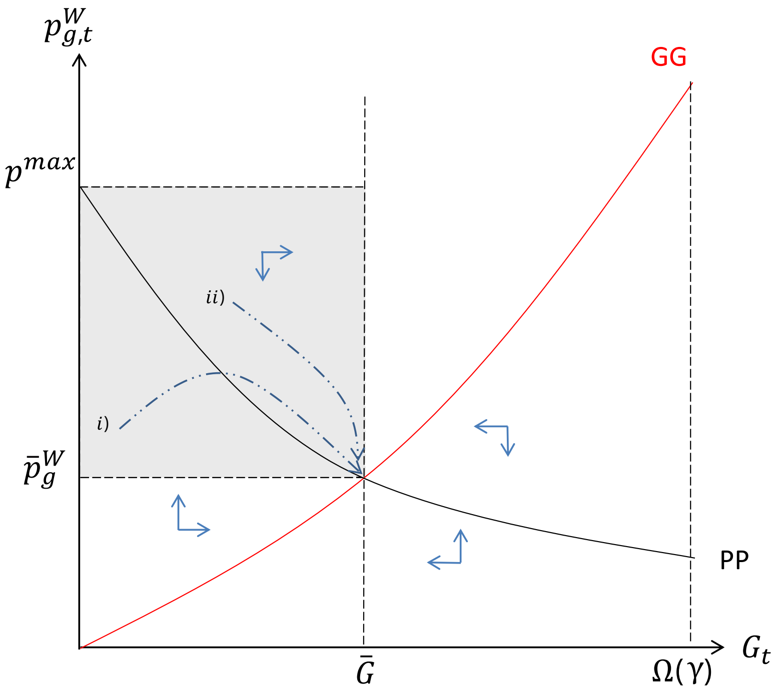

Fig. 2 Phase diagram with $\gamma \in (0, \bar{\gamma})$

process entails that the return of capital R_{t+1} in the North increases with pollution. The lifetime income of a northern agent born in t is therefore an increasing function of the relative price of good g and of the pollution stock. We can rewrite the indirect utility function by using Eq. (15):

$$V^N(p_{g,t}^W, G_t) = C_2 + \left(\alpha_g \frac{1+\alpha_b\beta}{\alpha_b - \alpha_g}\right) \ln\left(p_{g,t}^W\right) + \beta(1-\alpha_g)\ln(\Upsilon(G_t)), \tag{24}$$

with C_2 a constant whose value is given in "Appendix 3" and

$$\Upsilon(G_t) = \left[\frac{1+\left(\frac{T}{B}\right)^{\frac{1}{\alpha_b-\alpha_g}}\left(\frac{B^{\alpha_g}}{T^{\alpha_b}}\Psi(G_t)\right)^2}{1+\left(\frac{B}{T}\right)^{\frac{1}{\alpha_b-\alpha_g}}\left(\frac{B^{\alpha_g}}{T^{\alpha_b}}\right)\Psi(G_t)}\right].$$

The evolution of northern agents' welfare across generations is driven by the transitional dynamics of the world relative price and of the pollution stock. From the dynamical system presented in Lemma 1 and after defining the two loci GG $\equiv \{(p_{g,t}^W, G_t) : G_{t+1} = G_t\}$ and PP $\equiv \{(p_{g,t}^W, G_t) : p_{g,t+1}^W = p_{g,t}^W\}$, the transitional dynamics can be depicted in this phase diagram (see details in "Appendix 3").

Without damage, the usual dynamics such that the relative price of the capital intensive good decreases over time due to the capital accumulation process would always hold for standard initial conditions.[11] However, considering the negative impact of pollution on the stock of physical capital, this situation does not necessarily occur. Indeed, as illustrated in

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[11] In absence of pollution damage $\gamma = 0$, the PP locus is a horizontal line defined by $p^{max} \equiv \bar{p}_g^W$ and the dynamics of both pollution and the relative price are always increasing as long as the initial conditions on capital stock and pollution define an economy with $p_0^W < \bar{p}_g^W$ and $G_0 < \bar{G}$.

the phase diagram, when the initial level of pollution is not too high ($G < \bar{G}$) and the initial relative price is between $\bar{p}_g^W$ and p^{max} (i.e., the shaded area), the continuous upward trend of the world relative price of the green good no longer occurs. More precisely, we observe that while pollution is still increasing over time, the relative price of g can either increase for some periods and then decrease over time, or decrease for all periods along the convergence to the long-term state. This downward trend of the world relative price comes from the fact that the negative effect of pollution on the price through damages overtakes the direct positive effect of capital accumulation over time.

We study the evolution of the welfare of successive northern generations over time for such unusual dynamics and obtain the following proposition.

Proposition 2 *Under Assumptions 1–3 and $\gamma < \bar{\gamma}$, there exists a set of initial conditions K_0^N, K_0^S and G_0 such that, when β is sufficiently low, the welfare of successive generations is (i) first increasing but then decreasing over time, or (ii) always decreasing over time.*

Proof Directly obtained using the phase diagram depicted in Fig. 2 with Eq. (24). ☐

When the transitional path follows an upward trend in both pollution and the world price of the green good, the utility of successive generations increases over time. However, when the transitional path exhibits increasing pollution and a decreasing world price of g, two competing effects on northern agents' welfare are at work. The decrease in the world relative price of goods harms their welfare by reducing their wages, while the increase in pollution improves their welfare by increasing the returns on savings. When agents are very patient (β high), they highly value their consumption during retirement; hence, the utility of successive generations is still increasing along the transitional path even though environmental quality and the relative price of goods are deteriorating. However, when agents are sufficiently impatient (β low), the South's vulnerability prevents the continuous improvement of welfare in the North economy, and the welfare of successive generations actually falls.[12]

The fact that the welfare of northern generations is falling over time characterizes intergenerational inequity, as the lifetime utility of a given generation is lower than those of the previous generations. This result reveals that in an international trade context, climate change can cause intergenerational inequity even in an economy that would be completely preserved from its direct negative consequences.

Corollary 1 *Under Assumptions 1–3 and $\gamma < \bar{\gamma}$, there exists a set of initial conditions K_0^N, K_0^S and G_0 such that, when β is sufficiently low, the higher vulnerability of the South to climate change is a source of intergenerational inequity in the North.*

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[12] If the North were vulnerable to the direct effects of climate change in our setting, an additional negative effect on wages and interest rates would exist. Thus, it would make the decrease in the welfare of successive generations even more likely.

4.2 Long-Run Implications

In the long run, the economy achieves a stationary state in which the global stock of GHG and the stock of capital are stabilized. The welfares of all generations are thus identical at this state, meaning that there is no longer any intergenerational inequity issue. However, the long-term analysis enables us to obtain a full picture of how the South's vulnerability to pollution affects the northern agents' welfare. In this section, we examine the impact of a permanent increase in the South's vulnerability γ on the welfare of a northern generation, once the final steady state is achieved.

For that, we evaluate the indirect utility function (23) at the initial steady state and we totally differentiate the expression with respect to γ. The welfare effects are given by the following expression[13]:

$$Sign\left[\frac{dV^N}{d\gamma}\right] = Sign\left[\left(K^N - Y_b^N\right)\frac{\partial p_g^W}{\partial \gamma} + \frac{K^N(R^N-1)(1-\alpha_g)}{\alpha_b-\alpha_g}\frac{\partial p_g^W}{\partial \gamma}\right]. \tag{25}$$

The consequences of the South's vulnerability on northern agents' welfare consist of two effects, both operating through variations in the world relative price of the green good: a terms of trade effect (or ToT effect), captured by the first term of Eq. (25), and a dynamic (in)efficiency effect (or DyE effect), captured by the second term of Eq. (25). We study the direction and the magnitude of these two effects in the following subsections.

4.2.1 Terms of Trade Effect

The terms of trade effect depends on the specialization of regions. A net exporter of the green good suffers from a decrease in the world relative price of this good, while a net importer benefits from it.

We determine the pattern of trade in the presence of pollution costs by studying the net position of the North with regard to its exports of the brown good, denoted by e_b^N and equal to $Y_b^N - K^N$. As we do not consider the existence of debt or international capital mobility, we cannot observe a trade imbalance. As a result, when the North is a net exporter of the green good, the South is a net exporter of the brown good (and conversely). Using Eqs. (1), (6) (13), (15) and (17), we obtain[14]:

$$e_b^N = -e_b^S = \left[(B)^{\frac{1-\alpha_g}{\alpha_b-\alpha_g}} - (T)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}}\Psi(\gamma)\right] \equiv e_b^N(\gamma). \tag{26}$$

The vulnerability of the South to climate change γ has therefore a clear impact on the specialization of countries. More precisely, letting $\varepsilon_{G/\gamma} = \frac{\partial G(\gamma)}{\partial \gamma}\frac{\gamma}{G(\gamma)}$ represent the elasticity of the stationary stock of pollution to the South's vulnerability, we derive the following proposition.

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[13] Details are provided in "Appendix 4".

[14] For the rest of the analysis, we define $\Psi(\gamma, \bar{G}(\gamma)) \equiv \Psi(\gamma)$.

Proposition 3 *Under Assumptions 1–3 and* $|\varepsilon_{G/\gamma}| < 1/2$, *there exists a threshold* $\hat{\gamma}(\beta) \in (0, \bar{\gamma})$ *such that* $e_b^N(\hat{\gamma}(\beta)) = 0$. *At the long-term equilibrium, the North is a net exporter of the green good if* $\gamma < \hat{\gamma}(\beta)$, *and of the brown good if* $\hat{\gamma}(\beta) < \gamma < \bar{\gamma}$.

Proof See "Appendix 5". ☐

The elasticity of the stationary pollution stock $\bar{G}(\gamma)$ to the South's vulnerability γ must not be too high to ensure that an increase in vulnerability positively affects the damage in the South economy along the steady state ($\partial\Psi(\gamma)/\partial\gamma < 0$). Given this requirement, we reveal that the magnitude of natural disasters, captured by γ, alters the specialization of countries along the steady state. This result is due to two effects of γ on the capital stock of regions, represented by the following expressions.[15]

$$K^N = \frac{\beta}{1+\beta}(1-\alpha_b)A_b^N \left(\frac{\bar{p}_g^W A_g^N}{A_b^N} \right)^{\frac{\alpha_b}{\alpha_b - \alpha_g}} \Lambda_b^{\alpha_b};$$

$$K^S = \Psi(\gamma)\frac{\beta}{1+\beta}(1-\alpha_b)A_b^S \left(\frac{\bar{p}_g^W A_g^S}{A_b^S} \right)^{\frac{\alpha_b}{\alpha_b - \alpha_g}} \Lambda_b^{\alpha_b}.$$

First, an increase in the South's vulnerability γ has a direct effect on the South [through $\Psi(\gamma)$]. Provided that $|\varepsilon_{G/\gamma}| < 1/2$, γ acts as a negative productivity effect that translates into a fall in wages, hence reducing savings and the accumulation of physical capital in this region. Second, as capital becomes scarcer in the South, the world relative price of the capital intensive good (i.e., b) increases, or equivalently, the world relative price of the green good decreases ($\partial p_g^W/\partial\gamma < 0$). Therefore, this effect harms agents' wages and implies decreases in their savings and in the capital stock in both regions. In the end, the capital stock of each region is affected negatively by the climate damages occurring in the South, but the degradation is worse in this latter region. As a result, the North becomes relatively more capital abundant when the South's vulnerability to climate change increases.

When γ is high enough (i.e., $\bar{\gamma} > \gamma > \hat{\gamma}(\beta)$), the capital scarcity in the South is so large that the North has a comparative advantage in the polluting—capital intensive—sector. Even if the North is relatively more productive in the non-polluting sector, when environmental disasters are sufficiently important, the capital "endowment" differences are much stronger and become the main determinant of specialization. Therefore, damages from climate change distort the allocation of resources in favor of green production in the South, and brown production in the North. Even if free trade is a way to efficiently allocate resources, the presence of pollution costs can imply that the allocation of resources does not necessarily correspond to the intuitive situation where countries are specialized in the sector in which they have the highest relative productivity.

Note that the threshold $\hat{\gamma}(\beta)$ from which the comparative advantage of the North changes depends on the preferences for the future β. The more agents value their consumption when old, the higher their capital accumulation is and hence the higher the pollution stock. Thus,

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[15] These expressions are obtained from the capital market equilibrium in each country and Eq. (8) along the steady state.

β favors the negative effect on the South, and hence, the North's specialization in the brown production ($\hat{\gamma}(\beta)$ decreases with β).

From Proposition 3 indicating the specialization of each region, we can determine the sign of the terms of trade effect, i.e., the welfare implications of the fall in the world relative price of the green good due to a larger vulnerability going though the patterns of trade. It is the purpose of the following proposition.

Proposition 4 *Under Assumptions* 1–3, $|\varepsilon_{G/\gamma}| < 1/2$, *when* $\gamma < \hat{\gamma}(\beta)$ (*resp.* $\bar{\gamma} > \gamma > \hat{\gamma}(\beta)$), *the northern agents' welfare decreases* (*resp. increases*) *through the terms of trade channel when the South's vulnerability* γ *increases.*

Proof See "Appendix 5". ☐

The sign of the terms of trade effect depends on the level of the South's vulnerability γ.[16] When the South's vulnerability is low, the North is a net exporter of the green good g in the long run, so that the decrease in the relative price of g deteriorates its terms of trade and hence the welfare of northern agents. Conversely, when the South's vulnerability is high, the North is a net exporter of the brown good b so that the decrease in the relative price of g improves its terms of trade and its welfare.

4.2.2 Dynamic (In)efficiency Effect

The dynamic (in)efficiency effect depends on the dynamic efficiency properties of the North's competitive equilibrium. To examine this effect, we pay particular attention to the northern capital stock that maximizes the social welfare in the North, i.e., satisfying $R^N = 1$.[17] With overlapping generations, an increase in capital accumulation in the long run contributes positively to agents' welfare if there is dynamic efficiency and is damaging otherwise. Dynamic efficiency corresponds to situations in which the savings rate of agents is low, meaning that they under-invest in capital compared to the socially optimal solution. An increase in capital accumulation therefore enhances agents' welfare in this case. However, as shown previously, damages from climate change occurring in the South lead to a decrease in the world relative price of the green good, which reduces northern workers' wages and their ability to save. In this way, the South's vulnerability to climate change harms the capital accumulation in the North and affects the northern agents' welfare. This relation is what we call the dynamic (in) efficiency effect, whose direction is summarized in the following proposition.

Proposition 5 *Let* $\tilde{K}^N$ *be the efficient stock of capital in the North and* $K^N \equiv K^N(\beta, \gamma)$. *Under Assumptions* 1–3, $|\varepsilon_{G/\gamma}| < 1/2$, *there exists a threshold* $\tilde{\gamma}(\beta) \in (0, \bar{\gamma})$ *such that* $K^N(\beta, \tilde{\gamma}(\beta)) = \tilde{K}^N$. *When* $\bar{\gamma} > \gamma > \tilde{\gamma}(\beta)$ (*resp.* $\gamma < \tilde{\gamma}(\beta)$), *the welfare in the North economy decreases* (*resp. increases*) *through the dynamic* (*in*)*efficiency effect when the South's vulnerability to global pollution* γ *increases.*

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[16] Note that if we had assumed that the South has a comparative advantage in the green production in the absence of damages, $\hat{\gamma}$ would be equal to zero for all β, and the ToT effect would always be positive.

[17] We consider that an efficient allocation of resources in the North is given by the solution of a social planner program that maximizes the welfare of northern agents when all northern generations are treated equally (i.e., the social discount factor is equal to zero). In the absence of population growth, the optimal stationary capital ratio is such that the marginal product of capital is equal to 1.

Proof See "Appendix 6". ☐

On the one hand, the condition $\bar{\gamma} > \gamma > \tilde{\gamma}(\beta)$ corresponds to the case in which the North economy is at a dynamically efficient equilibrium or in other words, in which the stock of capital is lower than the capital maximizing northern social welfare. In this case, an increase in the South's vulnerability reinforces the existing under-accumulation of capital in the North compared to the optimal allocation, which implies that northern agents' welfare deteriorates.

On the other hand, when the North is at a dynamically inefficient equilibrium ($\gamma < \tilde{\gamma}(\beta)$), damages in the South reduce the over-accumulation of capital, and we find that this situation improves northern agents' welfare. The reason is that these agents highly value their consumption when old (sufficiently to over-accumulate capital), and by reducing the stock of physical capital, damages increase the return on their savings, which benefits them.

The fact that the North is at a dynamically efficient or inefficient equilibrium ($\gamma \lesseqgtr \tilde{\gamma}(\beta)$) depends logically on individuals' time preference β. Indeed, this parameter determines the importance agents attach to their future and hence the extent of their savings and their capital accumulation. We can extend Proposition 5 according to this key parameter.

Corollary 2 *Under Assumptions 1–3, $|\varepsilon_{G/\gamma}| < 1/2$ and $\gamma < \bar{\gamma}$, there exists a threshold $\bar{\beta}$ such that $\tilde{\gamma}(\bar{\beta}) = 0$. When agents in the world economy are sufficiently impatient with $\beta < \bar{\beta}$, an increase in the South's vulnerability always reduces northern agents' welfare through the dynamic (in)efficiency effect.*

Proof Under Assumptions 1–3, $|\varepsilon_{G/\gamma}| < 1/2$ and $\gamma < \bar{\gamma}$, the threshold $\tilde{\gamma}(\beta)$ is increasing with β and $\tilde{\gamma}(0) < 0$. Thus, there exists a unique threshold $\bar{\beta}$ such that $\tilde{\gamma}(\bar{\beta}) = 0$. When $\beta < \bar{\beta}$, we have $\tilde{\gamma}(\beta) < 0$, meaning that the condition to observe a positive dynamic (in) efficiency effect, $\gamma < \tilde{\gamma}(\beta)$, never holds. ☐

As long as northern agents sufficiently value their young age ($\beta < \bar{\beta}$), the North economy under-accumulates physical capital in the absence of damage. As damages harm capital accumulation, an increase in damages always causes welfare to fall in the North. Therefore, in this case, the vulnerability of the South to climate change always leads to a negative dynamic (in)efficiency effect on welfare in the North.

On the contrary, when $\beta > \bar{\beta}$, the sign of the dynamic (in)efficiency effect depends on the vulnerability of the South to climate change. Indeed, this condition implies that in the absence of damage, the North over-accumulates capital such that either scenario can emerge. An increase in climate damages in the South improves or reduces northern agents' welfare, depending on the vulnerability to pollution γ. Figure 3 illustrates this case, by plotting $\tilde{K}^N$ and K^N as a function of γ when $\beta > \bar{\beta}$. We find that, even when agents' preferences would lead to an over-accumulation of capital in the absence of damage, the dynamic (in) efficiency effect on welfare is negative as long as the vulnerability of the South is high (i.e., $\bar{\gamma} > \gamma > \tilde{\gamma}$).

4.2.3 Net Effect on Long-Term Welfare

After examining the two effects through which the South's vulnerability to climate change affects the northern agents' welfare, we question its net aggregate effect. These two effects

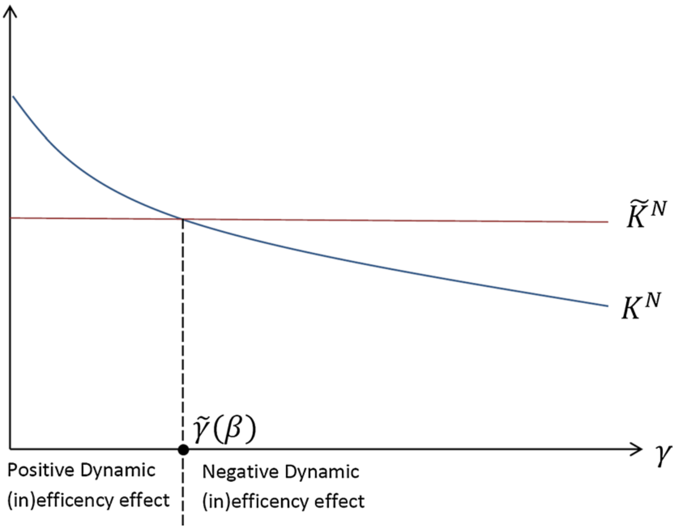

Fig. 3 Effect of an increase in γ on the North's capital stock for $\gamma < \bar{\gamma}$ and $\beta > \bar{\beta}$

may oppose or reinforce each other. As represented in Fig. 4, the terms of trade effect is negative if $\gamma < \hat{\gamma}(\beta)$ ($ToT-$) and positive otherwise ($ToT+$), while the dynamic efficiency effect is negative if $\gamma > \tilde{\gamma}(\beta)$ ($DyE-$) and positive otherwise ($DyE+$). This section aims to give some insight into the different possible scenarios in order to determine the net effect of the South's vulnerability on the welfare in the North. For this purpose, we rewrite Eq. (23), representing the northern agents' welfare, as a function of the stationary world relative price p_g^W only.

$$V^N(p_g^W) = C_1 + \ln\left(p_g^W\right)\left(\frac{\alpha_g(1+\beta) - \beta(1-\alpha_b)}{\alpha_b - \alpha_g}\right). \tag{27}$$

In this way, we clearly identify a condition on β that determines the global effect on welfare.

Proposition 6 *Under Assumptions 1–3, let* $|\varepsilon_{G/\gamma}| < 1/2$ *and* $\gamma < \bar{\gamma}$, *there exists a threshold* $\hat{\beta} = \alpha_g/(1-\alpha_b-\alpha_g)$ *with* $\tilde{\gamma}(\hat{\beta}) > 0$. *When* $\beta < \hat{\beta}$ (*resp.* $\beta > \hat{\beta}$), *once the final steady state is achieved, the welfare of a generation in the non-vulnerable economy decreases* (*resp. increases*) *with the South's vulnerability* γ.

Figure 4 summarizes the results presented in Propositions 4–6 and in Corollary 2.

When $\beta = \hat{\beta}$, the long-run welfare in the North does not depend on the South's vulnerability γ because the terms of trade and the dynamic (in)efficiency effects exactly offset each other. However, the damages from climate change in the South are always detrimental to northern agents' welfare as long as they sufficiently value their young age with respect to their old age ($\beta < \hat{\beta}$).

Therefore, we conclude that northern agents would benefit from an action preventing or minimizing the damages from climate change occurring in the South, when agents' preferences for the present is not too low. This recommendation is in line with Schenker and Stephan (2014), for whom an adaptation to climate change in the South funded by North may benefit to the donor. However, while this result is conditional upon the fact that the South's vulnerability deteriorates the terms of trade for North in Schenker and Stephan (2014), it

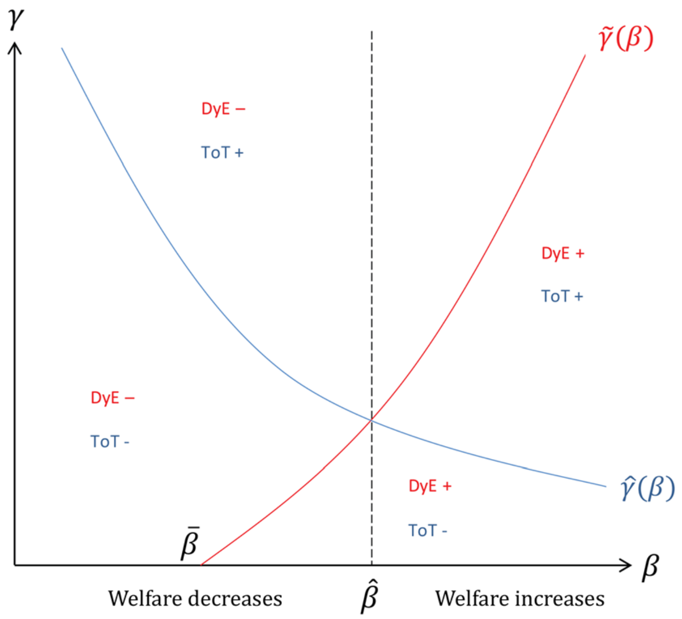

Fig. 4 Effect of an increase in γ on the welfare in the North for $\gamma < \bar{\gamma}$

holds in our paper even in the case in which the evolution in the terms of trade is in favor of the North.

To provide some insight into the likelihood of the cases in which the northern agents' welfare decreases or increases with the South's vulnerability to climate change, we calibrate the model in order to test the condition $\beta < \hat{\beta}$. In the real business cycle literature, the quarterly psychological discount factor is estimated as 0.99 (see Cooley 1995; de la Croix and Michel 2002). In our two period model, a period is equivalent to 40 years. Thus, β corresponds to $0.99^{4\times40} = 0.2$. Then, in order to calibrate $\hat{\beta}$, we use the results of Acemoglu and Guerrieri (2008), who compute the capital shares of different industries with United States data from the National Income and Product Accounts (NIPA). These authors find average capital shares in 2005 of 0.29 in the low capital intensity sectors and 0.499 in the high capital intensity sectors. With these figures, $\hat{\beta} = 1.37$ meaning that the condition $\beta < \hat{\beta}$ always holds for values of the parameters of technology and preferences that fit empirical observations. In other words, for realistic calibrations of the model, the northern agents' welfare always decreases with the South's vulnerability to climate change in the long run.

5 Conclusion and Discussion on Policy Implications

This paper explores the consequences of the unequal distribution of climate change damages in the world. Using a multi-sector dynamic general equilibrium model, we discuss how the damages from climate change occurring in a vulnerable country (South) can spill over to a non-vulnerable country (North) through international trade. We identify that the negative effects of global pollution on the South have harmful consequences for the North in the short and in the long run, as long as northern agents sufficiently value their welfare when young. In the short run, the damages from climate change in the South may represent a source of intergenerational inequity in the North, in the sense that northern agents' welfare decreases over generations. The reason is that natural disasters in the South lead to negative income effects for southern agents that harm their physical capital accumulation. In this way, damages modify the world relative price of goods and hence northern agents' income. In the long run, we find that for realistic calibrations of the model, the northern agents' welfare is always affected negatively by the damages from climate change in the South, even if the North is not directly vulnerable to it. This negative effect of the damages in the South on the northern economy comes from two possible effects (one or both): a deterioration of the terms of trade of the North—whose comparative advantage can evolve with climate change—and an under-accumulation of capital in the North entailed by the modifications of world prices.

Overall, the international community has become increasingly aware of the importance of public interventions and international cooperation in preventing the welfare loss resulting from climate change. Our analysis reinforces this idea by showing that in a world with free trade, there can be strong economic incentives for countries—even if their exposure to the direct effects of climate change is low—to fight against this global phenomenon (i.e., invest in mitigation) and to provide assistance to countries that are more vulnerable to climate change (i.e., help them to adapt).

Logically, questions arise about the kinds of policy to implement and their acceptability. We provide a brief discussion about these key issues in the following paragraphs. However, note that we do not formulate detailed policy prescriptions, because doing otherwise would require some adjustments of the model that we leave for future research.

The North's action could take the form of contributions to climate funds supporting developing countries' adaptation to climate change and/or of technological transfer programs such as the clean development mechanism (CDM), for example.[18] Regardless of the form of the action, it would entail a cost for the North, which would be readily accepted by the population if it is more than compensated by the benefits of exchanging with a country less affected by environmental damages.

The distribution of these benefits can be unequal across time and across populations, and hence create obstacles to the acceptance of such policies. In this paper, we point out that in the short run, agents do not always perceive the negative effect of foreign damages from climate change at the beginning of the convergence to the long-term state. The North may indeed experience a welfare improvement for some generations before pollution and the resulting damages become too important and hence make northern agents' welfare decline over time. Consequently, the implementation of costly measures may generate conflicts between agents living at different periods of time.

Moreover, as underlined by Karp and Rezai (2014), when looking at the acceptability of a policy, one crucial conflict is that between the different types of agents or generations alive when the policy is first implemented. In this vein, Chiroleu-Assouline and Fodha (2005) examine intergenerational distributional aspects of environmental taxes and determine the conditions to have an environmental reform that improves welfare for the generations bearing it. We examine this issue in "Appendix 7" and find that the benefits of an environmental policy introduced by the North may differ between the young and the old generations alive in the North when implementing the policy. We identify conditions such that fewer damages in the South always improve the welfare of the young by increasing their labor income whereas this situation may decrease the welfare of the elderly by reducing the return on capital. Therefore, a conflict between the two generations can emerge while discussing policy implementation, even if its aggregate impact is positive.

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[18] In a recent study, Ayong Le Kama and Pommeret (2017) emphasize the importance of devoting money to the CDM in order to control emissions abroad and hence reinforce the efficiency of adaptation measures implemented in the domestic economy.

Policy measures against climate change, especially those focusing on foreign countries, may face low public support if their benefits are not well perceived. However, some economic benefits of these policies may exist even for a country relatively sheltered from the direct effects of climate change, as suggested by the costs of climate change spreading through trade that we show. Given the necessity of public support to establish such a policy and the aforementioned two potential sources of misperception, it appears that clearly assessing the economic benefits associated with the different climate policies represents a key challenge for the future. Thus, we think that taking into account the indirect effects of climate change occurring through trade when examining further the economic consequences of a policy against climate change is an interesting avenue for future research.

In particular, it would be interesting to examine the implications of a carbon tax in this international trade context with unequal vulnerability to climate change. In this paper, we have left aside instruments such as a tax on the brown sector because it could affect the countries' comparative advantages and would therefore be much more complex to analyze. However, understanding how to design carbon pricing in an international context is crucial. The effects of a carbon tax depend on its structure and hence require careful study, which is why we leave it for future research.

Finally, climate change-induced migration may also represent a key issue to study in this framework, as the higher vulnerability of the South to climate change implies a larger need for southern agents to migrate. Our model omits from such consideration in order to propose an analysis tightly focused on international trade mechanisms. However, making the present model more suitable for this question would constitute an interesting line of research.

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Appendix

Appendix 1: Proof of Lemma 1

Using (6) and (14), we have

$$\begin{aligned} & L_{b,t}^N + \left(\frac{A_b^N}{A_b^S}\right)^{\frac{\alpha_g}{\alpha_b-\alpha_g}} \left(\frac{A_g^S}{A_g^N}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}} \Psi(G_t) L_{b,t}^S \\ & = \frac{(1-\alpha_b)\beta}{(1+\beta)} \left(1 + \left(\frac{A_b^N}{A_b^S}\right)^{\frac{\alpha_g}{\alpha_b-\alpha_g}} \left(\frac{A_g^S}{A_g^N}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}} \Psi(G_t)\right). \end{aligned} \tag{28}$$

From the capital market equilibrium in each country and Eq. (8), we have

$$\begin{aligned}
k_{b,t+1}^N &= \left(\frac{p_{g,t+1}^W A_g^N}{A_b^N}\right)^{\frac{1}{\alpha_b-\alpha_g}} \Lambda_b, \\
k_{b,t+1}^S &= \left(\frac{p_{g,t+1}^W A_g^S}{A_b^S}\right)^{\frac{1}{\alpha_b-\alpha_g}} \Lambda_b,
\end{aligned}$$

and

$$\begin{aligned}
K_{t+1}^N &= \frac{\beta}{1+\beta}(1-\alpha_b)A_b^N \left(\frac{p_{g,t}^W A_g^N}{A_b^N}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}} \Lambda_b^{\alpha_b}, \\
K_{t+1}^S &= \frac{\beta}{1+\beta}(1-\alpha_b)A_b^S \Psi(G_t) \left(\frac{p_{g,t}^W A_g^S}{A_b^S}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}} \Lambda_b^{\alpha_b}.
\end{aligned}$$

Combining these equations with (10), we obtain

$$L_{b,t+1}^N = \frac{(1-\alpha_b)}{(\alpha_b-\alpha_g)}\left[-\alpha_g + \frac{\alpha_b\beta}{1+\beta}(1-\alpha_g)A_b^N \left(\frac{A_b^N}{A_g^N}\right)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}} \left(\frac{(p_{g,t}^W)^{\alpha_b}}{p_{g,t+1}^W}\right)^{\frac{1}{\alpha_b-\alpha_g}} \Lambda_b^{\alpha_b-1}\right]$$

and

$$L_{b,t+1}^S = \frac{(1-\alpha_b)}{(\alpha_b-\alpha_g)}\left[-\alpha_g + \frac{\alpha_b\beta}{1+\beta}(1-\alpha_g)A_b^S \left(\frac{A_b^S}{A_g^S}\right)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}} \left(\frac{(p_{g,t}^W)^{\alpha_b}}{p_{g,t+1}^W}\right)^{\frac{1}{\alpha_b-\alpha_g}} \Lambda_b^{\alpha_b-1}\Psi(G_t)\right].$$

The key variable that guarantees world general equilibrium with international trade is the world relative price $p_{g,t}^W$. Equation (28) can be written as

$$\begin{aligned}
&-\frac{(1+\beta)\alpha_g}{\beta\alpha_b(1-\alpha_g)} + A_b^N \left(\frac{A_b^N}{A_g^N}\right)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}} \left(\frac{(p_{g,t}^W)^{\alpha_b}}{p_{g,t+1}^W}\right)^{\frac{1}{\alpha_b-\alpha_g}} \Lambda_b^{\alpha_b-1} \\
&+ \left(\frac{A_b^N}{A_b^S}\right)^{\frac{\alpha_g}{\alpha_b-\alpha_g}} \left(\frac{A_g^S}{A_g^N}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}} \Psi(G_t) \\
&\quad \left(-\frac{(1+\beta)\alpha_g}{\beta\alpha_b(1-\alpha_g)} + A_b^S \left(\frac{A_b^S}{A_g^S}\right)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}} \left(\frac{(p_{g,t}^W)^{\alpha_b}}{p_{g,t+1}^W}\right)^{\frac{1}{\alpha_b-\alpha_g}} \Psi(G_t)\Lambda_b^{\alpha_b-1}\right) \\
&= \frac{(\alpha_b-\alpha_g)}{\alpha_b(1-\alpha_g)}\left(1 + \left(\frac{A_b^N}{A_b^S}\right)^{\frac{\alpha_g}{\alpha_b-\alpha_g}} \left(\frac{A_g^S}{A_g^N}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}} \Psi(G_t)\right)
\end{aligned}$$

and after simplifications

$$A_b^N\left(\frac{A_b^N}{A_g^N}\right)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}}\left(\frac{(p_{g,t}^W)^{\alpha_b}}{p_{g,t+1}^W}\right)^{\frac{1}{\alpha_b-\alpha_g}}\Lambda_b^{\alpha_b-1}\left(1+\left(\frac{A_b^S}{A_b^N}\right)^{\frac{1-2\alpha_g}{\alpha_b-\alpha_g}}\left(\frac{A_g^N}{A_g^S}\right)^{\frac{1-2\alpha_b}{\alpha_b-\alpha_g}}\Psi(G_t)^2\right)$$
$$=\frac{\beta\alpha_b+\alpha_g}{\beta\alpha_b(1-\alpha_g)}\left(1+\left(\frac{A_b^N}{A_b^S}\right)^{\frac{\alpha_g}{\alpha_b-\alpha_g}}\left(\frac{A_g^S}{A_g^N}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}}\Psi(G_t)\right).$$

Lemma follows. ☐

Appendix 2: Existence and Unicity of Steady State, Proof of Proposition 1

Combining Eqs. (19) and (20) provided in Lemma 2, a steady state equilibrium $\bar{G}$ has to satisfy

$$\begin{cases} \mathcal{F}_1(\bar{G}) = \mathcal{F}_2(\bar{G}) \\ \bar{G} < \Omega, \end{cases}$$

with

$$\mathcal{F}_1(G) \equiv (G)^{\frac{\alpha_b-\alpha_g}{\alpha_b}}\left(\frac{\theta}{\eta}\frac{(1-\alpha_b)}{(\alpha_b-\alpha_g)}(A_b^N)^{\frac{1}{1-\alpha_b}}\right)^{\frac{-\alpha_b+\alpha_g}{\alpha_b}}$$
$$\times\left(\frac{(\beta\alpha_b+\alpha_g)\Upsilon(G)}{(1+\beta)}\left[1+\Psi(G)\left(\frac{B}{T}\right)^{\frac{1}{\alpha_b-\alpha_g}}\right]-\alpha_g\left[1+\left(\frac{B^{\alpha_g}}{T^{\alpha_b}}\right)^{\frac{1}{\alpha_b-\alpha_g}}\right]\right)^{\frac{-\alpha_b+\alpha_g}{\alpha_b}}$$

and

$$\mathcal{F}_2(G) \equiv \left(\frac{\beta\alpha_b+\alpha_g}{x\beta\alpha_b(1-\alpha_g)}\Upsilon(G)\right)^{\frac{\alpha_b-\alpha_g}{\alpha_b-1}}.$$

with

$$\Upsilon(G) = \frac{1+\Psi(G)\left(\frac{B^{\alpha_g}}{T^{\alpha_b}}\right)^{\frac{1}{\alpha_b-\alpha_g}}}{1+(\Psi(G))^2\left(\frac{1}{B}\right)^{\frac{1-2\alpha_g}{\alpha_b-\alpha_g}}(T)^{\frac{1-2\alpha_b}{\alpha_b-\alpha_g}}}.$$

The corresponding steady state relative price is given by:

$$\bar{p}_g^W = \mathcal{F}_1(\bar{G}).$$

The threshold Ω is given by $\Omega = \min\{G_1, G_2\}$ with G_1 and G_2 such that $L_b^S(T, G_1) = 0$ and $L_b^N(T, G_2) = 1$. Thus, the condition $G < \Omega$ guarantees that the equilibrium steady state is diversified, i.e. $0 < L_b^N, L_b^S < 1$.

We examine the properties of both functions on the interval $(0, \Omega)$. Under Assumptions 1–3, $\mathcal{F}_1(G)$ is increasing, with $\mathcal{F}_1(0) = 0$ and $\mathcal{F}_1(\Omega) > 0$. Concerning the function $\mathcal{F}_2(G)$, we have:

$$\frac{\mathrm{d}\mathcal{F}_2(G)}{\mathrm{d}G} = -\left(\frac{\beta\alpha_b + \alpha_g}{x\alpha_b\beta(1-\alpha_g)(1-\alpha_b)}\right)(\Upsilon(G))^{\frac{1-\alpha_g}{\alpha_b-1}}\frac{\mathrm{d}\Upsilon(G)}{\mathrm{d}G}.$$

We have to examine the sign of the term $\frac{\mathrm{d}\Upsilon(G)}{\mathrm{d}G}$, whose expression is the following:

$$\frac{\mathrm{d}\Upsilon(G)}{\mathrm{d}G} = \frac{-\Psi'(G)}{\left[1 + (\Psi(G)^2N\right]^2} \times \left[\Psi(G)^2MN + 2\Psi(G)N - M\right].$$

with $M = \left(\frac{B^{\alpha_g}}{T^{\alpha_b}}\right)^{\frac{1}{\alpha_b-\alpha_g}}$ and $N = \left(\frac{1}{B}\right)^{\frac{1-2\alpha_g}{\alpha_b-\alpha_g}}(T)^{\frac{1-2\alpha_b}{\alpha_b-\alpha_g}}$. The first part of the equation being positive, we focus on the second one. Under Assumption 3 and for $G < \Omega$, the second term is also positive, meaning that $\mathcal{F}_2(G)$ is downward sloping on the interval $(0, \Omega)$, with $\mathcal{F}_2(0) > 0$ and $\mathcal{F}_2(\Omega) > 0$. The condition to have a long-term diversified equilibrium is thus that:

$$\mathcal{F}_1(\Omega) > \mathcal{F}_2(\Omega). \tag{29}$$

The value for Ω is driven by γ. From (4), (15), (17) and (18), an increase in γ causes Ω to fall and hence causes $\mathcal{F}_1(\Omega)$ to fall and $\mathcal{F}_2(\Omega)$ to rise. When $\gamma = 0$, Ω tends to infinity with $\lim_{\Omega\to\infty}\mathcal{F}_1(\Omega) > \lim_{\Omega\to\infty}\mathcal{F}_2(\Omega)$. When γ tends to infinity, Ω is equal to zero with $\mathcal{F}_1(0) < \mathcal{F}_2(0)$. As a result, there exists a threshold $\bar{\gamma}$ such that when $\gamma < \bar{\gamma}$ the condition given by (29) holds. In this case, there exists a unique steady state: $\bar{G} \equiv \bar{G}(\gamma) \in (0, \Omega)$.

Appendix 3: Welfare Analysis: Short-Term Implications in the Non-vulnerable Economy

The indirect utility in the North is given by the following expression:

$$V^N(w_t^N, R_{t+1}^N, p_{g,t}^W, p_{g,t+1}^W) = \ln\left(\frac{1}{1+\beta}\frac{w_t^N}{p_{g,t}^W}\right) + \beta\ln\left(\frac{\beta}{1+\beta}\frac{R_{t+1}^N}{p_{t+1}^W}w_t^N\right).$$

We can express factor prices as functions of the relative price by using (9). In this way, we obtain a function that depends on the relative price only:

$$V^N(p_{g,t}^W, p_{g,t+1}^W) = C_1 + \left(\frac{\alpha_g + \alpha_b\beta}{\alpha_b - \alpha_g}\right)\ln\left(p_{g,t}^W\right) - \beta\left(\frac{1-\alpha_g}{\alpha_b-\alpha_g}\right)\ln\left(p_{g,t+1}^W\right),$$

with

$$\mathcal{C}_1 = \ln\left(\frac{1}{1+\beta}\right) + \beta \ln\left(\frac{\beta}{1+\beta}\right) + (1+\beta)\ln\left[(1-\alpha_b)A_b\left(\frac{A_g}{A_b}\right)^{\frac{\alpha_b}{\alpha_b-\alpha_g}}\Lambda_b^{\alpha_b}\right]$$
$$+\ \beta \ln\left[(1-\alpha_b)A_b\left(\frac{A_g}{A_b}\right)^{\frac{\alpha_b-1}{\alpha_b-\alpha_g}}\Lambda_b^{\alpha_b-1}\right].$$

As $p^W_{g,t+1}$ is a function of $p^W_{g,t}$ and G_t, using Eq. (15), we can also express the indirect utility as

$$V^N(p^W_{g,t}, G_t) = \mathcal{C}_2 + \left(\alpha_g \frac{1+\alpha_b\beta}{\alpha_b-\alpha_g}\right)\ln\left(p^W_{g,t}\right) + \beta(1-\alpha_g)\ln(\Upsilon(G_t)),$$

with

$$\mathcal{C}_2 = \mathcal{C}_1 - \beta(1-\alpha_b)\ln\left(\frac{\beta\alpha_b(1-\alpha_g)}{\beta\alpha_b+\alpha_g}\right).$$

To describe the dynamics of this model, we define the two loci $\mathrm{GG} \equiv \{(p^W_{g,t}, G_t) : G_{t+1} = G_t = G\}$ and $\mathrm{PP} \equiv \{(p^W_{g,t}, G_t) : p^W_{g,t+1} = p^W_{g,t} = p^W_g\}$. Using Lemma 1, we have:

$$\begin{aligned}\text{GG locus}:\ p^W_g &= (G)^{\frac{\alpha_b-\alpha_g}{\alpha_b}}\left(\frac{\theta}{\eta}\frac{(1-\alpha_b)}{(\alpha_b-\alpha_g)}(A^N_b)^{\frac{1}{1-\alpha_b}}\right)^{\frac{-\alpha_b+\alpha_g}{\alpha_b}}\\ &\times\left(\frac{(\beta\alpha_b+\alpha_g)\Upsilon(G)}{(1+\beta)}\left[1+\Psi(G)\left(\frac{B}{T}\right)^{\frac{1}{\alpha_b-\alpha_g}}\right]-\alpha_g\left[1+\left(\frac{B^{\alpha_g}}{T^{\alpha_b}}\right)^{\frac{1}{\alpha_b-\alpha_g}}\right]\right)^{\frac{-\alpha_b+\alpha_g}{\alpha_b}}\\ &= \mathcal{F}_1(G),\\ \text{PP locus}:\ p^W_g &= \left(\frac{\beta\alpha_b+\alpha_g}{x\beta\alpha_b(1-\alpha_g)}\Upsilon(G)\right)^{\frac{\alpha_b-\alpha_g}{\alpha_b-1}} = \mathcal{F}_2(G).\end{aligned} \tag{30}$$

The functions $\mathcal{F}_1(G)$ and $\mathcal{F}_2(G)$ are already defined in "Appendix 2", to derive the existence of the steady state. The dynamics in the North economy can be depicted by a phase diagram whose phase lines are given by GG and PP loci. Under Assumptions 1–3, the term $\Upsilon(G)$ is increasing in G for $G \in (0, \Omega)$ meaning that PP locus is downward sloping. Using the results provided in "Appendix 2", GG locus is upward sloping for $G \in (0, \Omega)$. Thus, the dynamics can be depicted in Fig. 2.

The transitional path depends on the initial conditions on the pollution stock $G_{t=0} \equiv G_0$ and on the price $p^W_{g,t=0} \equiv p^W_{g,0}$. The latter is given by the initial conditions on the capital stocks of North and South K^N_0 and K^S_0, and on pollution G_0. Indeed, from (8) and (10), we have $L^i_{b,t} \equiv L^i_b(K^i_t, p^W_{g,t})$. Replacing it in the equilibrium condition on the brown good market (14) and using (6), we have:

$$A^N_b L^N_b(K^N_t, p^W_{g,t}) + A^S_b L^S_b(K^S_t, p^W_{g,t})\Psi(G_t) = \frac{(1-\alpha_b)\beta}{1+\beta}\left(A^N_b + \Psi(G_t)A^S_b\right).$$

From this equality, we have:

$$p_{g,0}^{W} = \Theta(\underset{+}{K_0^N}, \underset{+}{K_0^S}, \underset{+}{G_0}),$$

with $\Theta(0, K_0^S, G_0) > 0$, $\Theta(K_0^N, 0, G_0) > 0$, $\Theta(0, 0, G_0) = 0$ and $\Theta(K_0^N, K_0^S, 0) > 0$. We focus on the case in which $G_0 < \bar{G}$, and $p_{g,0}^W < p^{max}$ with p^{max} the relative price of good in the absence of pollution. In that case, we can observe a transitional path with a decreasing trend in p_g^W if the initial conditions on K^S, K^N and G are such that the initial relative price $p_{g,0}^W$ is above the PP locus that prevails along the steady state. Finally, we can summarize this situation by the following conditions:

$$\left(\frac{\beta\alpha_b + \alpha_g}{\beta\alpha_b(1-\alpha_g)}\Upsilon(\bar{G})\right)^{\frac{\alpha_b}{\alpha_b-1}} \equiv \bar{p}_g^W < \Theta(K_0^N, K_0^S, G_0) < \left(\frac{\beta\alpha_b + \alpha_g}{\beta\alpha_b(1-\alpha_g)}\Upsilon(G_0)\right)^{\frac{\alpha_b}{\alpha_b-1}} \equiv p^{max} \tag{31}$$

and

$$G_0 < \bar{G}.$$

In the absence of damage ($\gamma = 0$), we have $\bar{p}_g^W = p^{max}$, meaning that the condition (31) never holds. Under Assumptions 1–3 and $\gamma < \bar{\gamma}$, $\Upsilon(G)$ is increasing in G. For all initial values $G_0 < \bar{G}$, we thus have $\bar{p}_g^W < p^{max}$. Given the properties of the function $\Theta(K_0^N, K_0^S, G_0)$ presented above, when $G_0 < \bar{G}$ there always exists a set of value (K_0^N, K_0^S) that satisfies inequality (31), such that we observe a decreasing trend in p_g^W over time.

Appendix 4: Welfare Analysis: Long-Term Implications in the Non-vulnerable Economy

The stationary indirect utility in the North is given by the following expression:

$$V(w^N, R^N, p_g^W) = \ln\left(\frac{1}{1+\beta}\frac{w^N}{p_g^W}\right) + \beta \ln\left(\frac{\beta}{1+\beta}\frac{R^N}{p^W}w^N\right) \equiv V^N. \tag{32}$$

Let $\omega^N = w^N/p_g^W$, from (32) it follows that:

$$Sign\left[\mathrm{d}V^N\right] = Sign\left[\left(\frac{\mathrm{d}\omega^N}{\mathrm{d}p_g^W} + \frac{\beta}{1+\beta}\frac{\omega^N}{R^N}\frac{\mathrm{d}R^N}{\mathrm{d}p_g^W}\right)\mathrm{d}p_g^W\right].$$

Using the fact that

$$\mathrm{d}\omega^N/\mathrm{d}p_g^W = (p_g^W)^{-1}(\mathrm{d}w^N/\mathrm{d}p_g^W - w^N/p_g^W)$$

and

$$\frac{\beta}{1+\beta}w^N = K^N,$$

we have:

$$Sign\left[\mathrm{d}V^N\right] = Sign\left[\left(\frac{K^N}{R^N}\frac{\mathrm{d}R^N}{\mathrm{d}p_g^W} - \frac{w^N}{p_g^W} + \frac{\mathrm{d}w^N}{\mathrm{d}p_g^W}\right)\mathrm{d}p_g^W\right]. \tag{33}$$

In each country, the gross domestic product is equal to the total revenue of capital and workers:

$$\left[Y_b^N + Y_g^N p_g^W\right] = w^N + R^N K^N. \tag{34}$$

By differentiating this equation, we obtain:

$$\begin{aligned} Y_g^N \mathrm{d}p_g^W &= \mathrm{d}w^N + K^N \mathrm{d}R^N, \\ \frac{\mathrm{d}w^N}{\mathrm{d}p_g^W} &= Y_g^N - \frac{K^N \mathrm{d}R^N}{\mathrm{d}p_g^W}. \end{aligned} \tag{35}$$

Combining (34) and (35), we obtain:

$$\frac{\mathrm{d}w^N}{\mathrm{d}p_g^W} = \frac{w^N + R^N K^N - Y_b^N}{p_g^N} - \frac{K^N \mathrm{d}R^N}{\mathrm{d}p_g^W}. \tag{36}$$

Moreover, using Eq. (6), we have:

$$\frac{\mathrm{d}w^N}{\mathrm{d}p_g^W} = \frac{\alpha_b}{\alpha_b - \alpha_g}\frac{w^N}{p_g^W}; \quad \frac{\mathrm{d}R^N}{\mathrm{d}p_g^W} = -\frac{1-\alpha_b}{\alpha_b - \alpha_g}\frac{R^N}{p_g^W}. \tag{37}$$

Using (36) and (37), Eq. (33) can be written as:

$$Sign\left[\frac{dV^N}{\mathrm{d}p_g^W}\right] = Sign\left[\frac{K^N}{R^N}\frac{\mathrm{d}R^N}{\mathrm{d}p_g^W} - \frac{w^N}{p_g^W} + \frac{w^N + R^N K^N - Y_b^N}{p_g^N} - \frac{K^N \mathrm{d}R^N}{\mathrm{d}p_g^W}\right]$$

and after simplifications, we have:

$$Sign\left[\frac{dV}{\mathrm{d}p_g^W}\right] = Sign\left[\frac{K^N}{R^N}\frac{\mathrm{d}R^N}{\mathrm{d}p_g^W}(1 - R^N) + \frac{R^N K^N - Y_b^N}{p_g^N}\right].$$

Using (37),

$$Sign\left[\frac{dV^N}{\mathrm{d}p_g^W}\right] = Sign\left[\left(\frac{-(1-\alpha_b)(1-R^N)K^N}{\alpha_b - \alpha_g} + R^N K^N - Y_b^N\right) \times \frac{1}{p_g^W}\right].$$

Finally, this expression can be expressed as follows:

$$Sign\left[\frac{dV^N}{\mathrm{d}p_g^W}\right] = Sign\left[\left(\frac{(1-\alpha_g)R^N K^N - K^N(1-\alpha_g) + K^N(\alpha_b - \alpha_g)}{\alpha_b - \alpha_g} - Y_b^N\right) \times \frac{1}{p_g^W}\right],$$

and we obtain the indirect utility given by Eq. (25).

Appendix 5: Pattern of Trade Along the Steady State, Proof of Propositions 3 and 4

Using (26), the pattern of specialization along the steady state is the following:

(a) When $\Psi(\gamma) > \frac{(B)^{\frac{1-\alpha_g}{\alpha_b-\alpha_g}}}{(T)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}}}$, North is a net exporter of the green good.

(b) When $\Psi(\gamma) < \frac{(B)^{\frac{1-\alpha_g}{\alpha_b-\alpha_g}}}{(T)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}}}$, North is a net exporter of the brown good.

The pattern of specialization depends on how the undamaged part of production $\Psi(\gamma)$ responds to the South's vulnerability γ. For $\gamma = 0$, $\Psi(\gamma) = 1$ and the scenario (a) is observed. For $\gamma = \bar{\gamma}$, under Assumption 3, North is perfectly specialized in the brown good and the scenario (b) is observed.

To examine more precisely the conditions that lead the North to specialize in the brown good, we have to pay particular attention to how the undamaged part of production $\Psi(\gamma)$ evolves with γ. From (4), we have:

$$\frac{\partial \Psi(\gamma)}{\partial \gamma} = -(G(\gamma))^2 \frac{\Psi(\gamma)}{1 + \gamma (G(\gamma))^2} \left(\varepsilon_{G/\gamma} + \frac{1}{2} \right),$$

with $\varepsilon_{G/\gamma} = \frac{\partial G(\gamma)}{\partial \gamma} \frac{\gamma}{G(\gamma)}$. Thus, when $|\varepsilon_{G/\gamma}| < 1/2$, we have $\frac{\partial \Psi(\gamma)}{\partial \gamma} < 0$ and there exists a threshold $\hat{\gamma}(\beta) \in (0, \bar{\gamma})$ such that $\Psi(\hat{\gamma}(\beta)) = \frac{(B)^{\frac{1-\alpha_g}{\alpha_b-\alpha_g}}}{(T)^{\frac{1-\alpha_b}{\alpha_b-\alpha_g}}}$.

The way the damages from climate change affect the North along the steady state depends largely on capital accumulation, which is driven by agent's time preference β. We have thus defined the steady state value for pollution as $\bar{G} \equiv G(\gamma, \beta)$ and the threshold on γ as a function of β. We have $\frac{\partial G(\gamma,\beta)}{\partial \beta} > 0$. This result is derived by using functions $\mathcal{F}_1$ and $\mathcal{F}_2$, provided in "Appendix 2", whose intersection gives the steady state equilibrium $G(\gamma, \beta)$. Following an increase in β, $\mathcal{F}_1(G)$ shifts downward while $\mathcal{F}_2(G)$ shifts upward, meaning that the equilibrium value $G(\gamma, \beta)$ increases. As $G(\gamma, \beta)$ is an increasing function of β, from (26), $\hat{\gamma}(\beta)$ decreases with β. Then, the propositions follow. □

Appendix 6: Proof of Proposition 5

The social welfare in the North, defined by a social planner that treats all northern generations equally, is maximized for an allocation that satisfies that the marginal product of capital is equal to one (i.e., $R^N = 1$). Using (6) along the steady state, we obtain that a marginal product of capital equal to one implies $k_b^N = \left(A_b^N \alpha_b\right)^{\frac{1}{1-\alpha_b}}$. From the equilibrium on the brown good market along the steady state, $K^N = Y_b^N$, and (1), we have:

$$K^N = \frac{A_b^N \left(k_b^N\right)^{\alpha_b} (1 - \alpha_b)}{A_b^N (1 - \alpha_g) \alpha_b \left(k_b^N\right)^{\alpha_b - 1} + \alpha_g - \alpha_b}. \tag{38}$$

The stock of capital that guarantees a steady state marginal product of capital equal to one in the North is thus:

$$K^N = A_b^N \left(A_b^N \alpha_b\right)^{\frac{\alpha_b}{1-\alpha_b}} \equiv \tilde{K}^N.$$

From (8), (13), (20) and the equilibrium on the capital market along the steady state, $K^N = s^N$, the stationary competitive stock of capital is:

$$K^N = \frac{\beta}{1+\beta}(1-\alpha_b)\left(A_b^N\right)^{\frac{1}{1-\alpha_b}} \left(\frac{\beta\alpha_b(1-\alpha_g)}{(\beta\alpha_b+\alpha_g)\Upsilon(G(\gamma,\beta))}\right)^{\frac{\alpha_b}{1-\alpha_b}} \equiv K^N(\gamma,\beta).$$

Under Assumptions 1–3 and for $\gamma < \bar{\gamma}$ and $|\varepsilon_{G/\gamma}| < 1/2$, $\Upsilon(G(\gamma,\beta))$ increases with γ which implies $\partial K^N/\partial\gamma < 0$. Indeed, Υ depends on γ only through the undamaged part of production Ψ. From Assumptions 1–3 and for $\gamma < \bar{\gamma}$, the term Υ decreases with Ψ and for $|\varepsilon_{G/\gamma}| < 1/2$ the undamaged part of production falls with γ along the steady state.

The competitive stock of capital corresponds to those maximizing the social welfare in the North if and only if:

$$K^N(\gamma,\beta) = \tilde{K}^N \;\Leftrightarrow\; \frac{\beta}{1+\beta}(1-\alpha_b)\left(\frac{\beta(1-\alpha_g)}{(\beta\alpha_b+\alpha_g)\Upsilon(G(\gamma,\beta))}\right)^{\frac{\alpha_b}{1-\alpha_b}} = 1.$$

Under Assumptions 1–3 and for $\gamma < \bar{\gamma}$, there exists a unique value of γ that guarantees that the competitive stock of capital satisfied $R^N = 1$: $\tilde{\gamma}(\beta)$. When $\gamma > \tilde{\gamma}(\beta)$, $R^N > 1$ and $K^N < \tilde{K}^N$: there is under-accumulation of capital. Conversely when $\gamma < \tilde{\gamma}(\beta)$, $R^N < 1$ and $K^N > \tilde{K}^N$: there is over-accumulation of capital. Under Assumptions 1–3 and for $\gamma < \bar{\gamma}$, we have the following properties for $\tilde{\gamma}(\beta)$: $\tilde{\gamma}(\beta)$ increases with β and $\tilde{\gamma}(0) < 0$, meaning that there is under-accumulation of capital $\forall\,\gamma$ when $\beta = 0$. Given the fact that K^N is decreasing with γ, an increase in the South's vulnerability makes the competitive solution further to the efficient allocation in the first case and closer in the second case.

Appendix 7: Discussion on the Welfare Implications of a Decrease in Damages on Northern Generations

We do not formalize policy measures in our study but we can appreciate their potential benefits by examining the impacts of a variation in parameters θ and/or γ. We can suppose an investment in clean development mechanisms (CDM) that aims at mitigating emissions (i.e., decreasing the pollution intensity θ), or a contribution to climate funds supporting adaptation that consists in reducing the South's vulnerability (i.e., γ).

Leaving aside the financial cost of such an environmental policy, we provide some insight into the necessary conditions for its acceptability by the different generations alive when the policy is first implemented in the North. To this aim, we examine the distributive effect of an exogenous fall in damages (captured by a decrease in γ and/or θ) between consumption of young and old people at the steady state.[19]

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[19] A fall in θ reduces the damage by its negative impact on the long run stock of pollution. A fall in γ reduces the damage in the long run provided that the elasticity of long run pollution stock to γ is not too high.

The following expressions correspond to the welfare—indirect utility—of the young ($V^{Ny}(p_g^W)$) and of the old ($V^{No}(p_g^W)$) northern agents that coexist along the steady state:

$$V^{Ny}(p_g^W) = C^y + \frac{\alpha_g}{\alpha_b - \alpha_g}\ln(p_g^W); \quad V^{No}(p_g^W) = C^o + \frac{\alpha_b + \alpha_g - 1}{\alpha_b - \alpha_g}\ln(p_g^W), \tag{39}$$

with $C^y = \ln\left(A_b^N(1-\alpha_b)\Lambda_b^{\alpha_b}\left[\frac{A_g^N}{A_b^N}\right]^{\frac{\alpha_b}{\alpha_b-\alpha_g}}\right)$ and $C^o = \ln\left(\left(A_b^N\right)^2\alpha_b(1-\alpha_b)\Lambda_b^{2\alpha_b-1}\left[\frac{A_g^N}{A_b^N}\right]^{\frac{2\alpha_b-1}{\alpha_b-\alpha_g}}\right)$.

From the previous analysis, we know that an—exogenous—decrease in damages in the long run increases the relative price p_g^W (see Lemma 1 with Assumptions 1–3). Using the indirect utility functions given in (39), we obtain:

Result 1 *Under Assumptions 1–3, let* $|\varepsilon_{G/\gamma}| < 1/2$ *and* $\gamma < \bar{\gamma}$. *At the steady state, when the damages from climate change on the South decrease, the welfare of the northern young always increases while the welfare of the northern elderly decreases (resp. increases) for* $\alpha_b + \alpha_g < 1$ *(resp.* $\alpha_b + \alpha_g > 1$*).*

This result gives intuitions about how northern agents coexisting at a given period of time are affected by a reduction in environmental damages in the South. We reveal that it could create a potential conflict between the two generations—young and old—as they are not affected in the same way by the spillover effects of pollution.

As the damages in the South lower the return of labor, it necessarily decreases the first period utility of young northern agents. However, in the absence of direct damages from climate change in the North, the elderly benefits from the damages in the South when capital intensity is not too high ($\alpha_b + \alpha_g < 1$). Under this condition, they have no economic incentive to accept and to contribute to the funding of an environmental policy aiming at proving assistance to the South. Even if such measures may generate benefits in the future, these benefits would occur beyond the lifespan of the elderly generation.

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ORIGINAL ARTICLE

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Pollution in a globalized world: Are debt transfers among countries a solution?

Marion Davin[1] | **Mouez Fodha**[2] | **Thomas Seegmuller**[3]

[1]CEE-M, CNRS, INRAe, SupAgro, University of Montpellier, Montpellier, France

[2]Paris School of Economics, PjSE, University Paris 1 Pantheon-Sorbonne, Paris, France

[3]CNRS, AMSE, Aix Marseille University, Marseille, France

Correspondence
Mouez Fodha, Paris School of Economics, PjSE, University Paris 1 Pantheon-Sorbonne, 48 Boulevard Jourdan, 75014 Paris, France.
Email: mouez.fodha@univ-paris1.fr

Abstract

We analyze the effects of a debt relief, that is, a decrease in public debt of a low-income country financed by a high-income country, on environmental quality. Under perfect mobility of assets, the debt relief increases the overall capital stock, and environmental quality when public abatements are sufficiently efficient. Welfare in both countries can also improve. Under a weak mobility of assets, capital does no more increase in the richest country, but environmental quality can improve. This comes from a crowding-out effect of debt in the high-income country, which does no more take place when the mobility of assets is significant.

KEYWORDS

capital market integration, global pollution, overlapping generations, public debt

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F43, H23, Q56

1 | INTRODUCTION

The trend in CO_2 emissions predicts a global temperature increase of more than 3°C by the end of the century with severe consequences. In addition, climate change is accompanied by other global environmental problems such as plastic waste, pesticides, and persistent organic pollutants (POPs), which can cause both locally and globally damaging effects. Loss of agricultural yield, loss of biodiversity, sea level rise, climate migration, extreme weather events, increased health problems, etc. are all the phenomena that will increase, and the brunt of the economic damages will be probably borne by poorest countries (Mendelsohn et al., 2006; Schelling, 1992). To achieve a 1. 5°C consistent pathway, to limit the discharge of plastic waste into the oceans, or to stop the accumulation of POPs in the atmosphere, the international community calls for immediate global response.

Environmental objectives are a particular concern for low-income countries in which these challenges are compounded by high levels of external economic vulnerability and public debt. They recurrently use public debt to absorb the impact of external macroeconomic shocks and, recently, of more frequent natural disasters. In turn, higher levels of public debt associated with weak macroeconomic situation increase fiscal pressure and constrain the capacity of countries to address vulnerabilities and to mitigate pollution.[1] According to IMF classification, a large part of low-income countries presents a high risk of experiencing a debt crisis, which underlines the importance to compose with countries debt profiles to address environmental challenges.[2]

When we examine the diversity of instruments used to provide climate finance, debt transfers, in the form of debt reliefs granted by developed countries to developing ones, currently represent only an insignificant proportion of financing strategies (see Table 1 built by Fenton et al., 2014). Yet, debt transfers are justified if they enhance the environmental quality and economic variables (consumption, savings, capital, etc.) simultaneously.

Does a debt transfer in favor of low-income countries a relevant macroeconomic policy to promote pollution reduction? This question is of interest when international environmental policies have not been implemented to fight pollution effectively. Therefore, classical economic policies must regain legitimacy. This article contributes to this question by using a theoretical approach combining debt transfers and global pollution issues. We aim at analyzing the consequences of a debt transfer from high-income to low-income countries on pollution, GDP, and well-being. We only study second-best policies, without seeking to achieve optimality.

We develop a two-country overlapping generations (OLG) model with global pollution externalities. Production deteriorates the environmental quality, harming the welfare of future generations, but public abatement that linearly increases with income improves it. Total-factor productivity determines the country profile: we define the low-income (resp. the high-income) country as the one with the lower (resp. the higher) level of productivity. According to the empirical evidence, people of the richest country are the more patient and hence have the highest saving rate. Countries are also characterized by different levels of debts. Issuing public debt and tax on agents' income are used to finance public abatement and debt services. The overall debt remains constant, even after international debt transfers have taken place. This implies a constant global debt supply and rules out issues related to unsustainable global debt.

We study the environmental and economic consequences of a debt relief in favor of the low-income country, funded by the high-income country. Under perfect mobility of assets, the debt transfer implies a redistribution of income net of tax between the countries and modifies the debt burden and public abatement through a general equilibrium effect. When the interest rate is low, which is supported by several recent empirical studies (Ahn, 2003; Blanchard, 2019; Geerolf, 2018; Rachel & Summers, 2019), issuing more debt in the high-income country reduces taxation and increases savings. In this context, debt relief raises capital because this country has

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[1] Collard et al. (2015) show empirically the extent to which debt levels can be a limit for financing future investments. They propose a measure of maximum sustainable government debt for advanced economies, which strongly varies across countries.

[2] See the debt sustainability framework of IMF and World Bank for public and external debt sustainability analysis in low-income countries.

TABLE 1 Instrument used to fulfill climate finance commitments

Financial instruments	Amount (million, US$)	Share
Grants and related instruments	14,379.1	45.2%
Unknown	614.4	1.9%
Multiple	419.3	1.3%
Loans, guarantees, and insurance	14,840.2	46.7%
Debt relief	82.5	0.3%
Capital contribution	1457.4	4.6%
Total	31,792.9	100%

Note: From Fenton et al. (2014). Based on the data collected by the World Resource Institute http://go.nature.com.inshs.bib.cnrs.fr/rMhVxK.

the highest saving rate. Environmental quality increases because public abatements per unit of income are assumed to be sufficiently efficient. In this context, a debt relief can therefore be beneficial for both capital accumulation and the environment, but also welfare, when the interest rate is low. Therefore, our paper contributes to the literature that aims to rethink or redefine policies under low interest rates (Blanchard, 2019; Rachel & Summers, 2019).

We then analyze the robustness of these results when the mobility of assets is imperfect. To that extent, we consider the polar case without mobility. In this case, savings of each country should finance its own public debt. As a debt relief means that public debt increases in the high-income country and decreases in the low-income country, there is a crowding-out effect on capital in the former country, whereas we observe exactly the opposite effect in the last one. Environmental quality still improves if the effect of public abatement net of pollution raises sufficiently in the low-income country, which happens if debt in this country is high enough. Therefore, the main difference between perfect mobility of assets and weak mobility concerns the real side of the economy. The question is whether debt emission in country with high income can be financed or not by oversaving of the other country. If it is mostly not the case, capital does not raise in the high-income country because of a crowding-out effect.

Our paper contributes to two strands of the literature, namely the interplay between public debt and environmental quality, and the links between economic development and the environment in an international context. Connecting these two strands, we provide new intuitions about the effects of international transfers on welfare and the environment.

Debt financing has been introduced in dynamic models with environmental concerns (Bovenberg & Heijdra, 1998; Fernández et al., 2010; Heijdra et al., 2006). Debt policy only makes possible to redistribute welfare gains from future to existing generations: there is no debt financing for environmental protection. Fodha and Seegmuller (2012, 2014) and Fodha et al. (2018) analyze debt financing schemes for public and private mitigation. They show that efficient environmental fiscal reforms may be designed. This literature, however, considers closed economies, which is a limitation as capital markets are interconnected and globalized, as climate and some global pollution issue.

Our work complements prior contributions that deal with global environmental issues in international frameworks. First, John and Pecchenino (1997) focus on the effects of cooperation between two countries in mitigating global pollution. Their approach considers neither capital nor savings arbitrage, and they only assume lump-sum transfers between countries. They conclude that the developing countries must be compensated for their environmental expenditures. In our article, we focus on financial markets and debt reduction. The new thing is that the transfer we highlight goes through the financial market and has effects through the debt service reduction. The second is the work of Bednar-Friedl et al. (2010). Countries differ in their levels of public debt per capita. They find that if the country that reduces its emissions permits is a net creditor to the world economy, the domestic welfare costs are smaller. While in this work mitigation efforts are exogenous, we differ by studying in detail the effect of debt transfers. Third, Muller-Furstenberger and Schumacher (2017) propose a dynamic model where all agents contribute to a global externality, but only those in a specific region suffer from it. They show that if agents suffering from the externality are low income, they may be stuck in an environmental poverty trap, but capital market integration helps to escape from the trap. We differ from this article by considering public expenditure for the environment and by examining the influence of public debt on saving and capital accumulation.

The literature has also questioned the characteristics of international transfers to protect the environment to see whether donor countries should prioritize technology transfers oriented toward mitigation or adaptation (Barañano & San Martín, 2015; Sakamoto et al., 2017). A related literature considers the interplay between environmental policy and development aid transfers in low-income countries and conclude that these transfers are in general ineffective (Bretschger & Suphaphiphat, 2014; Eyckmans et al., 2016). In our article, we depart from this literature as we limit aid transfers to untied debt cancellation.

Finally, in our paper, debt relief is undertaken without any counterpart (i.e. debt relief in return for improved environmental protection). Our model does not consider debt for nature swaps (Cassimon et al., 2011, 2014; Deacon & Paul, 1997). The literature on economic development underlines the inefficiencies of this type of aid as soon as donor country monitoring is not put in place. The risk of inefficiency of this policy is all the higher as the recipient country faces problems of quality governance, or extreme poverty. These issues are discussed in depth in Azam and Laffont (2003). They show how the optimal aid contract is complicated when institutional details of the real world are considered.

The rest of this paper is organized as follows. Section 2 presents the two-country OLG model with environmental externalities. Section 3 defines the configuration of perfect mobility of assets. Section 4 studies the robustness under imperfect mobility. Section 5 provides concluding remarks. Technical details are relegated to Appendix A.

2 | THE MODEL

The world consists of two competitive economies indexed by $i \in \{D, F\}$. Within each country, a new generation of two-period lived agents is born at each period of time. Therefore, two generations are alive in each period t: the workers and the retired people. In each country, the population size is constant and normalized to one. There is no mobility of labor between countries, whereas we will first assume that there is perfect mobility of the assets and a unique final good, as in Persson (1985). Perfect capital mobility can be seen as an approximation of countries with highly integrated financial markets and few capital controls. In a second step, we will extend our analysis to a world with imperfect mobility of assets.

2.1 | Global environmental quality

Global environmental quality evolves as the opposite of the global stock of pollution, representing the stock of greenhouse gases in the atmosphere or the stock of plastics in the oceans. We measure this aggregate environmental quality by an index, which deteriorates with emission flow from production in each country and is enhanced by public abatement measures. Abatement could be reforestation, plastic waste management, anti-pollution devices (filters, particulate filter), insulation of buildings, energy transition, waste collection and sorting or carbon capture and sequestration technologies. Following John and Pecchenino (1994), Ono (2002), or Mariani et al. (2010), we interpret E as a measure of the amenity value of the environmental quality.

Global environmental quality E_t evolves according to

$$E_{t+1} = (1 - m)E_t + \phi_D g_{Dt} + \phi_F g_{Ft} - \theta_D y_{Dt} - \theta_F y_{Ft}, \tag{1}$$

where y_{it} and g_{it} represent, respectively, production and public abatement of country i, and $E_0 > 0$. The pollution flow resulting from production is given by the emission factor $\theta_i > 0$ and efficiency of abatement is given by factor $\phi_i > 0$. We keep these parameters different between the two countries.

In the absence of human activity, the quality of the environment has an autonomous level of zero; the parameter $m \in (0, 1)$ measures the speed of reversion of environmental quality to this level.[3] For some current environmental issues, natural "cleaning up" of the environment is not possible. This last point is all the more important as the environment is already highly polluted. A high level of pollution compromises a favorable evolution of the environment, as shown by the case of plastics in the oceans and the loss of marine biodiversity it induces, or the consequences of climate change on biodiversity; nature cannot restore the natural state, unless huge investments are undertaken (Muller-Furstenberger & Schumacher, 2017).

2.2 | Firms

In each country, firms use capital and labor for the production of a unique final good, which is the *numéraire*. The technology used is Cobb-Douglas. As there is no labor mobility and labor input equals one in each country, the production function writes $y_{it} = A_i k_{it}^{\alpha}$, where k_{it} denotes

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[3] We could, however, also interpret m as pollution absorption, and consider Equation (1) as a linear approximation of a more complicated relationship between production, public abatement, and the quality of the environment. For instance, let P_t be the stock of pollution, such that $P_{t+1} = (1 - m)P_t - \phi_D g_{Dt} - \phi_F g_{Ft} + \theta_D y_{Dt} + \theta_F y_{Ft}$. Then assume that the environmental quality index is defined by $E_t = \widetilde{E} - P_t$, with $\widetilde{E} \geqslant 0$ is the long-term natural value of E. We obtain

$$\widetilde{E} - E_{t+1} = (1 - m)(\widetilde{E} - E_t) - \phi_D g_{Dt} - \phi_F g_{Ft} + \theta_D y_{Dt} + \theta_F y_{Ft}.$$

The equation is equivalent to

$$E_{t+1} = (1 - m)E_t + m\widetilde{E} + \phi_D g_{Dt} + \phi_F g_{Ft} - \theta_D y_{Dt} - \theta_F y_{Ft}.$$

By taking $\widetilde{E} = 0$, we find (1).

capital, $A_i > 0$ the country-specific productivity, and $\alpha \in (0, 1)$ the capital share in income. Profit maximization gives

$$w_{it} = (1 - \alpha)A_i k_{it}^{\alpha}, \tag{2}$$

$$R_{it} = \alpha A_i k_{it}^{\alpha-1}, \tag{3}$$

with w_{it} the wage and R_{it} the return of capital in country i.[4]

2.3 | Households

A generation born at period t derives utility from consumption when young c_{it} and old d_{it+1}, and from environmental quality at both periods. Accordingly, the lifetime utility is given by

$$\ln c_{it} + \delta_i \ln E_t + \beta_i(\ln d_{it+1} + \delta_i \ln E_{t+1}), \tag{4}$$

where $\beta_i \in (0, 1)$ denotes the discount factor in country i, and $\delta_i \geqslant 0$ the vulnerability to pollution stock. We assume that these preference parameters are country specific, which means that $\beta_D \neq \beta_F$ and $\delta_D \neq \delta_F$. On one hand, heterogeneity between the discount factors β_i of the different countries is supported by empirical studies (Lawrance, 1991; Tanaka et al., 2010; Wang et al., 2016). On the other hand, δ_i aggregate both sensitivity and vulnerability to climate change which are also different among high-income and low-income countries (Mendelsohn et al., 2006; Schelling, 1992). Environmental quality when young E_t and old E_{t+1} is taken as given by agents. It acts as a pure externality in the utility function.

When young, each agent inelastically supplies one unit of labor and receives real wage w_{it}. A lump-sum tax τ_{it} is levied on this income. Net income, $w_{it} - \tau_{it}$, is shared between consumption c_{it} and savings s_{it}. Consumption when old d_{it+1} is entirely financed by the remunerated savings. Therefore, the two budget constraints faced by an agent born at period t write

$$c_{it} + s_{it} = w_{it} - \tau_{it}, \tag{5}$$

$$d_{it+1} = R_{it+1}s_{it}. \tag{6}$$

A young agent maximizes her utility (4) considering the two budget constraints (5) and (6). We obtain $d_{it+1} = \beta_i R_{it+1} c_{it}$ and deduce that

$$s_{it} = \frac{\beta_i}{1 + \beta_i}(w_{it} - \tau_{it}),\ c_{it} = \frac{1}{1 + \beta_i}(w_{it} - \tau_{it}),\ d_{it+1} = \frac{\beta_i}{1 + \beta_i}R_{it+1}(w_{it} - \tau_{it}). \tag{7}$$

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[4] For simplification and considering the duration of a period, we assume full depreciation of capital after one period of use.

2.4 | Government

The government engages in public abatement g_{it} to directly reduce pollution. The government collects lump-sum tax τ_{it} on workers and uses bonds as debt instrument b_{it}. Its expenditures include repayment of debt and interest payments, as well as public spendings that correspond here to public abatement. In addition to the engagement in abatement, the government can use debt to postpone the financing of expenditures and modify current taxes to increase income.

In each country, the government faces the following budget constraint:

$$b_{it+1} = R_{it} b_{it} - \tau_{it} + g_{it}, \tag{8}$$

with the initial public debt level $b_{i0} \geqslant 0$ given. In this paper, we consider public debt as being a target and a policy instrument, and we thus assume a constant level of debt $b_{it} = b_i > 0$. Concerning public expenditures on environmental protection, review of data from Eurostat and IMF shows a disparity between countries and relative stability over time when expenditure is evaluated in terms of GDP.[5] We thus assume that the ratio of public spending over GDP is constant and country specific, that is, $g_{it} = g_i y_{it}$, with $g_i > 0$.

Introducing these different ingredients in the government budget (8), we obtain

$$\tau_{it} = (R_{it} - 1) b_i + g_i y_{it}. \tag{9}$$

Taxation is endogenous and varies to satisfy the government budget constraint at each period of time.

We aim at studying the effect of a debt relief, that is, a reallocation of debt between the two countries, in the long run. We will in particular analyze the effect of a debt relief through an increase of b_D which allows to decrease b_F. Such a policy implies a redistribution of income net of tax between the two countries, as the tax paid in each country depends on b_i. However, we will see that the effects of a debt transfer differ from a standard redistribution of income because it goes through different channels. Indeed, while a debt transfer directly modifies taxes, it also modifies the debt burden, that is, the interest rate, and public abatement through a general equilibrium effect.

Considering debt issues and its interplay with the global environment in an integrated world, the degree of capital market integration is important. We start by studying the effect of a debt relief on environmental quality and productive capital of each country when the mobility of assets is perfect. Then, we will analyze the robustness of the result when the mobility of assets becomes imperfect.

3 | PERFECT MOBILITY OF ASSETS

As international capital mobility is assumed to be perfect, foreign and domestic assets yield the same rate of return. Market clearing also requires world savings equal to world investment:

$$R_{Dt} = R_{Ft}, \tag{10}$$

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[5] See also Ercolano and Romano (2018) for a study on spending for environmental protection in Europe.

$$s_{Dt} + s_{Ft} = k_{Dt+1} + b_{Dt+1} + k_{Ft+1} + b_{Ft+1}. \tag{11}$$

Given the public abatements and the production technologies in each country, the law of motion for environmental quality (1) is given by

$$E_{t+1} = (1-m)E_t + (\phi_D g_D - \theta_D)A_D k_{Dt}^{\alpha} + (\phi_F g_F - \theta_F)A_F k_{Ft}^{\alpha}, \tag{12}$$

and $E_t > 0$. Using (3), Equation (10) means that

$$k_{Ft} = k_{Dt}\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}. \tag{13}$$

We consider a domestic economy richer than the foreign one. Numerous studies emphasize that the major part of the difference in incomes between high-income and low-income countries is due to differences in total factor productivity. We can refer to the survey by Caselli (2005) and the study by Hsieh and Klenow (2010). Moreover, in line with empirical evidences (Tanaka et al., 2010; Wang et al., 2016), wealthy population or population in wealthier countries is characterized by preferences with lower discount rate and thus tends to be more patient. We thus assume a domestic economy more patient than the foreign one.

Assumption 1. $A_D > A_F$ and $\beta_D > \beta_F$.

Despite this assumption on the productivities between countries, we do not impose any ranking on the respective debt levels, that is, b_D higher or smaller than b_F.

Substituting (2), (3), and (9) into (7), we obtain savings in both countries:

$$s_{it} = \frac{\beta_i}{1+\beta_i}\left[(1-\alpha-g_i)A_i k_{it}^{\alpha} - \left(\alpha A_i k_{it}^{\alpha-1} - 1\right)b_i\right]. \tag{14}$$

Using the condition of perfect mobility of capital (13), pollution evolves according to

$$E_{t+1} = (1-m)E_t + \left[\phi_D g_D - \theta_D + (\phi_F g_F - \theta_F)\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}\right]A_D k_{Dt}^{\alpha}. \tag{15}$$

We ensure that environmental quality is positive for each level of m and at a steady state. Moreover, public spending over GDP g_i should be low enough to ensure positive savings whatever the level of debt. Accordingly, we assume:

Assumption 2. $\phi_D g_D - \theta_D + (\phi_F g_F - \theta_F)\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}} > 0$ and $g_i < 1-\alpha$ for $i = D, F$.

The first condition implies that efficiencies of abatements per unit of income should be sufficiently high with respect to emission rates. In particular, the benefit resulting from one unit of abatement has to be larger than the environmental damage resulting from one unit of production at least in one country. This seems a reasonable condition because we consider the environmental quality that is perceived by agents. In this way, governments invest in abatement activities that especially target environmental issues while pollution is simply a side effect of the aggregate production process. Therefore, the marginal benefit of abatement can be assumed to be relatively higher than the marginal damage of production. The second condition means that public spending over GDP should be lower than the labor share of income. In other words, the fiscal burden has to be lower than labor income to keep the wage net of taxes positive.

Using (13) and (14), the equilibrium on the asset market (11) rewrites:

$$k_{Dt+1}\left[1+\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}\right]=\left[\frac{\beta_D}{1+\beta_D}(1-\alpha-g_D)+\frac{\beta_F}{1+\beta_F}\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}(1-\alpha-g_F)\right]A_D k_{Dt}^{\alpha}$$
$$-\left(\frac{b_D}{1+\beta_D}+\frac{b_F}{1+\beta_F}\right)-\left(\frac{\beta_D}{1+\beta_D}b_D+\frac{\beta_F}{1+\beta_F}b_F\right)\alpha A_D k_{Dt}^{\alpha-1}\equiv G(k_{Dt}). \tag{16}$$

Given $E_0 > 0$ and $k_{D0} > 0$, Equations (15) and (16) drive the dynamics of the economy. In fact, (16) determines the sequence of $(k_{Dt})_{t\geqslant 0}$ and given it, (15) determines the sequence of $(E_t)_{t\geqslant 0}$.

We note that $G(k_{Dt})$ is a strictly increasing and concave function with $G(0) < 0$ and $\lim_{k_{Dt}\to+\infty} G(k_{Dt})/k_{Dt} < 1+\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}$. Therefore, one can easily show that for b_D and b_F not too high, the dynamics of k_{Dt} is characterized by two steady states $k_l > 0$ and $k_h(>k_l)$, where k_l is unstable ($G'(k_l) > 1+\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}$) and k_h is stable ($G'(k_h) < 1+\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}$). See also Figure 1.

Using (15), we easily see that E_j, the level of environmental quality associated with k_j for $j = \{h, l\}$, is given by

$$E_j=\frac{1}{m}\left[\phi_D g_D-\theta_D+(\phi_F g_F-\theta_F)\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}\right]A_D k_j^{\alpha}, \tag{17}$$

which is positive under Assumption 2. As $dE_{t+1}/dE_t = 1-m \in (0,1)$ and both k_{Dt} and E_t are predetermined variables, the steady state (k_l, E_l) is an unstable saddle, whereas (k_h, E_h) is stable.

We now focus on the effect of debt relief which means an increase in debt b_D and a decrease in b_F such that $b_D + b_F$ does not change, that is, $db_D = -db_F = db > 0$, on the stable steady

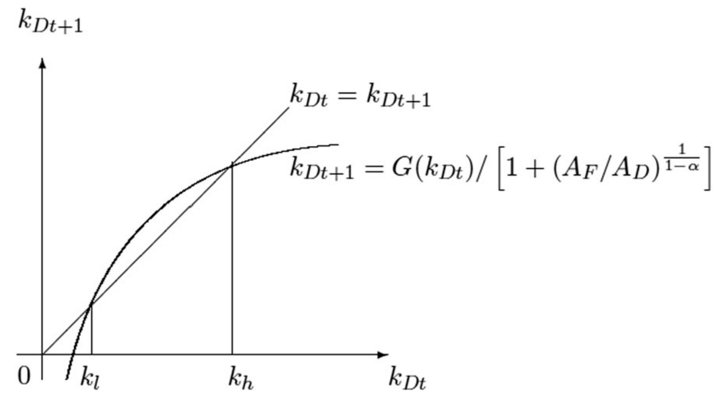

FIGURE 1 Dynamics of capital.

state (k_h, E_h). We examine whether debt relief increases capital. It is of particular interest because, according to (17), it also improves environmental quality. We deduce the following proposition:

Proposition 1. *Under Assumptions 1 and 2, a debt relief implies:*

1. *An increase of k_h and E_h if $R_h < 1$ (low interest rate);*
2. *A decrease of k_h and E_h if $R_h > 1$ (high interest rate).*

with $R_h \equiv \alpha A_D k_h^{\alpha-1}$.

Proof. See Appendix A.1. □

As the economies share a common asset market, the debt transfer has no direct crowding-out effect on capital: the larger level of public debt in country D is exactly compensated by the lower level in country F. The effects entailed by the policy therefore go through the variation in taxes. As the domestic country is more patient ($\beta_D > \beta_F$), the debt transfer entails an increase in capital stock only when there is a low interest rate ($R_h < 1$). In that case, issuing more debt reduces the fiscal pressure. The transfer of debt is associated with a transfer of income favorable for the patient economy. Of course, we have the opposite result when countries are characterized by a high interest rate ($R_h > 1$).

Because the efficiencies of public abatements per unit of income are sufficiently high with respect to emissions rates, environmental quality evolves in the same direction than capital. Public abatements therefore play a crucial role in our analysis. If they were not sufficiently efficient and if they did not respond to income, environmental quality and GDP per capita could not improve together.

Because debt relief is efficient to increase environmental quality and capital when there is over-accumulation, we now examine the conditions to have such a configuration. Let us define $\tilde{k}_D$ such that $G'(\tilde{k}_D) = 1 + \left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}$. Of course, $\tilde{k}_D < k_h$ and $R_h = \alpha A_D k_h^{\alpha-1} < 1$ if $\alpha A_D \tilde{k}_D^{\alpha-1} < 1$. As $G'(\tilde{k}_D)$ is decreasing in $\tilde{k}_D$ and using (16), this last condition is satisfied if:

$$\begin{aligned}&\frac{\beta_D}{1+\beta_D}(1-\alpha-g_D) + \frac{\beta_F}{1+\beta_F}\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}(1-\alpha-g_F)\\&+(1-\alpha)\left(\frac{\beta_D}{1+\beta_D}b_D + \frac{\beta_F}{1+\beta_F}b_F\right)(\alpha A_D)^{-\frac{1}{1-\alpha}} > 1 + \left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}.\end{aligned} \tag{18}$$

We deduce the following corollary:

Corollary 1. *Under Assumptions 1 and 2, and inequality (18), a debt relief implies an increase of k_h and E_h.*

By inspection of inequality (18), a debt relief improves the environmental and real sides of the economy if A_D is sufficiently low (given the ratio A_F/A_D), the saving rates $\beta_i/(1+\beta_i)$ and the debt levels b_i are high enough.

It is also important to note that having low interest rate has a significant empirical support in macroeconomics (Ahn, 2003; Blanchard, 2019; Geerolf, 2018; Rachel & Summers, 2019), and can be explained by over-saving and secular stagnation, for instance. This means that Proposition 1 and Corollary 1 establish the relevance of debt relief to increase capital and environmental quality under some realistic conditions. When the cost of the debt is low ($R_h < 1$), the increase in debt in country D does not translate into a higher tax burden. Having such properties is interesting as this country is characterized by a higher saving rate than country F. In this way, environmental engagement increases following the policy. This also means that our paper contributes to this literature that suggests to rethink about fiscal policies when the interest rates are low (Blanchard, 2019; Rachel & Summers, 2019).

Considering that Corollary 1 holds, we then examine the effect of the debt transfer on the agent's welfare in both economies $i = D, F$. Using agent's consumption choices (7), its indirect utility V_{ih} evaluated at the stable steady state (k_h, E_h) is given by

$$V_{ih} = (1 + \beta_i)\ln(w_{ih} - \tau_{ih}) + \beta_i \ln(R_h) + (1 + \beta_i)\delta_i \ln(E_h) + \beta_i \ln\beta_i - (1 + \beta_i)\ln(1 + \beta_i). \tag{19}$$

Following a debt relief, E_h increases. Therefore, we have to investigate whether the utility associated with consumptions raises too or not. This is shown in the following corollary:

Corollary 2. *Under Assumptions 1 and 2, inequality (18) and $\alpha \geqslant 1/3$ and $R_h \geqslant 1/3$, a debt relief implies an increase in the welfare evaluated at the steady state (k_h, E_h) in country D, while the effect on the welfare in country F is positive only if preferences for environmental quality δ_F and/or debt level b_F are high enough.*

Proof. See Appendix A.2. ☐

When interest rate is low enough ($R_h < 1$), capital goes up in each country and the environment improves following the debt relief. Such capital improvement leads to opposite effects on the well-being, by improving wage and reducing the return of saving. At the same time, lower interest rate reduces the cost of debt. For country D, as long as the share of capital and interest rate satisfy $\alpha \geqslant 1/3$ and $R_h \geqslant 1/3$, which seems to be empirically relevant assumptions, the positive effects on income outweigh the negative effect associated with the lower return of saving. Accordingly, the welfare increases in country D because both the utility of consumptions and environmental quality raise. To observe an improvement of welfare in country F, additional conditions are required. Indeed, the effect of the policy on the utility for consumptions is not clear-cut. This is because the constraint to keep the aggregate level of debt constant implies that taxation may go up in the foreign economy. The reduction in the debt burden has to be sufficiently important to avoid such increase and/or the weight associated with environmental quality has to be sufficiently high to observe a rise in welfare effects in the foreign economy.

In a context of low interest rate and perfectly integrated capital market, a debt transfer from the patient to the impatient country is a way to increase capital stock and hence environmental engagement. This may increase the welfare in both countries. Note that even in a context with $R_h < 1$, keeping $b_D + b_F$ constant is important as it allows to avoid crowding-out effects. We can also underline that a simple transfer of income would not provide such welfare benefits. Indeed, if the domestic patient country transfers revenue to the foreign impatient country, the aggregate capital stock would go down, unless to mix such a transfer to conditions aiming at modifying behavior in the recipient country. We do not explore this kind of policy in our analysis.[6]

As a part of the problem of pollution in low-income countries could be related to their low efficiency in abatement activities, it is also possible to consider that the fall in debt cost entailed by the debt transfer could be used to improve this efficiency. This would be beneficial for global environment but could question the welfare benefit of the transfer for the foreign country. Indeed, in that scenario, the foreign country would not benefit from a lower fiscal burden, and this could make the transfer costly for the real side of the economy.

4 | IMPERFECT CAPITAL MOBILITY

Despite the increased importance of international capital flows, some countries are characterized by imperfect capital mobility, implying that foreign and domestic assets do not necessarily yield the same rate of return. External debt, defined as $k_{t+1}^i + b_{t+1}^i - s_t^i$, depends on the interest rate differential between countries. Market clearing always requires world savings equal to world investment.

To understand the difference between the effect of debt relief under perfect and imperfect mobility, we consider the limit case where the two countries are closed but share a common environment. We can use (7) to define the equilibrium on the asset market in each country $i = D, F$ as follows:

$$k_{it+1} + b_i = \frac{\beta_i}{1+\beta_i}\left[(1-\alpha)A_i k_{it}^{\alpha} - \tau_{it}\right]. \tag{20}$$

Using (3) and (9), we obtain

$$k_{it+1} = \frac{\beta_i}{1+\beta_i}(1-\alpha-g_i)A_i k_{it}^{\alpha} - \frac{b_i\beta_i}{1+\beta_i}\alpha A_i k_{it}^{\alpha-1} - \frac{b_i}{1+\beta_i} \equiv G_i(k_{it}). \tag{21}$$

Given the levels of capital in each country, the global level of environmental quality is still defined by the law of motion (12).

We note that $G_i(k_{it})$ is a strictly increasing and concave function with $G_i(0) < 0$ and $\lim_{k_{it}\to+\infty} G_i(k_{it})/k_{it} < 1$. We deduce that when b_i is not very high, in each economy, there are two steady states, the unstable one $k_{i1} > 0$, with $G_i'(k_{i1}) > 1$, and the stable one $k_{i2} (> k_{i1})$, with $G_i'(k_{i2}) \in (0, 1)$. As in the previous section, we focus on this last one to study the effect of the policy on the equilibrium of the global economy. We easily see that an increase of debt b_i decreases k_{i2}. Indeed, differentiating $k_{i2} = G_i(k_{i2})$, we deduce that

$$\frac{dk_{i2}}{db_i} = -\frac{1+\beta_i\alpha A_i k_{i2}^{\alpha-1}}{\left(1-G_i'(k_{i2})\right)(1+\beta_i)} \tag{22}$$

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[6] The acceptability of a transfer of income from foreign (less advanced) to domestic (advanced) economy is excluded.

has the opposite sign of db_i because $G_i'(k_{i2}) \in (0, 1)$. Here, countries do not share a common capital market, and as a result, the debt transfer affects capital stock through a direct crowding-out effect and an indirect income effect (whose sign depends on the level of the interest rate).[7] The first effect is more important. Therefore, a debt relief, which corresponds to an increase of debt b_D and a decrease of b_F, always implies a decrease of k_{D2} and an increase of k_{F2}.

Let E_2 be the stationary level of environmental quality associated with k_{D2} and k_{F2}. It is given by

$$E_2 = \frac{1}{m}\left[(\phi_D g_D - \theta_D)A_D k_{D2}^{\alpha} + (\phi_F g_F - \theta_F)A_F k_{F2}^{\alpha}\right]. \tag{23}$$

Since $m \in (0, 1)$, the steady state (k_{D2}, k_{F2}, E_2) is the only one stable. To ensure that environmental quality and the levels of capital are positive, Assumption 2 is replaced by

Assumption 3. $\phi_i g_i - \theta_i > 0$ and $g_i < 1 - \alpha$ for $i = D, F$.

Note that this assumption implies Assumption 2. As in the previous section, we focus on the effect of debt relief which means an increase of debt b_D and a decrease of b_F such that $b_D + b_F$ does not change, that is, $db_D = -db_F = db > 0$, on the stable steady state (k_{D2}, k_{F2}, E_2). Differentiating Equation (23), we get

$$\begin{aligned}\frac{dE_2}{db} = &-\frac{(\phi_D g_D - \theta_D)\alpha A_D k_{D2}^{\alpha-1}}{m}\frac{1 + \beta_D \alpha A_D k_{D2}^{\alpha-1}}{\Big(1 - G_D'(k_{D2})\Big)(1 + \beta_D)} \\ &+ \frac{(\phi_F g_F - \theta_F)\alpha A_F k_{F2}^{\alpha-1}}{m}\frac{1 + \beta_F \alpha A_F k_{F2}^{\alpha-1}}{(1 - G_F'(k_{F2}))(1 + \beta_F)}.\end{aligned} \tag{24}$$

We can rationalize that for a given level of k, we have $G_D(k) > G_F(k)$ because $\beta_D > \beta_F$ and the fiscal pressure (measured by b_i and g_i) in country D is not higher than in country F. This implies that k_{F2} is lower than k_{D2}. However, this is not enough to give a clear cut sign of dE_2/db. A positive sign of this expression is, however, obtained if $G_F'(k_{F2})$ is sufficiently close to 1.

Proposition 2. *Under Assumptions 1 and 3, and $\alpha(2 - \alpha) < 1$, there exists a stationary level $\widehat{k}_{F2}$ such that $G_F'(\widehat{k}_{F2}) = 1$ for a given level of $b_F = \widehat{b}_F$. For a slightly lower level of debt, we have $k_{F2} > \widehat{k}_{F2}$ but close to $\widehat{k}_{F2}$. In this case, a debt relief implies a decrease of k_{D2} and an increase of k_{F2} and E_2.*

Proof. See Appendix A.3. ☐

We deduce from this proposition that the two countries cannot benefit from the effect of the policy in terms of capital. Indeed, since the economies are closed, debt has a crowding-out effect on capital. When debt increases, less savings is devoted to finance capital investment, whereas when debt decreases, we have of course the opposite effect on capital. This explains that k_D decreases and k_F increases. When capital was perfectly mobile, this would not occur

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[7] Indeed, Equation (20) also writes $k_{it+1} + b_i = \frac{\beta_i}{1+\beta_i}[(1 - \alpha - g_i)A_i k_{it}^{\alpha} - (R_{it} - 1)b_i]$. We easily see that income increases or not with public debt if the interest rate is smaller or higher than one.

because the larger level of public debt in country D was financed by the excess of savings of country F.

As regards environmental quality, it improves if green public spendings net of pollution increases. Because public spendings over GDP are constant, green public spendings net of pollution linearly raises with the country's income. As a result, public environmental engagement increases in economy F, while effort in country D becomes lower. An improvement of environmental quality thus requires a sufficiently high difference between income variation in countries F and D. Then, Proposition 2 implies that the effect of the marginal increase of income in country F dominates the effect of the marginal decrease of income in country D. We note that it does not require a low interest rate for all countries, but a sufficiently high level of debt in country F.

Then, we can examine the effects of the transfer on the welfare when economies do not share a common capital market. Based on the indirect utility (19), it is easy to see that the welfare effects are not clear-cut. According to Proposition 2, labor income increases in country F and decreases in country D, while global environmental quality improves. At the same time, the transfer entails a direct effect on taxes which is negative in country D and positive in country F if the interest rate is lower than one. Reversely, the transfer increases taxes in country D and reduces it in country F if the interest rate is higher than one. Therefore, even if it is not clear-cut, an increase of welfare associated with the consumptions over the life cycle is more likely to occur in country F than in country D. In this last one, an increase of welfare would require a sufficiently high preference for the environmental quality. Therefore, the implementation of such a policy based on debt relief could depend on the acceptability of country D which could experience a decrease in income and welfare.

Our analysis allows to assess that debt relief can improve environmental quality, whatever the degree of integration between countries. Nevertheless, a difference emerges concerning the real side of the economy. This difference is important because it can condition the acceptability of the policy. Let us consider the relevant case with low interest rate ($R_h < 1$). When capital mobility is sufficiency high, the results presented in Proposition 1 prevail and both countries can benefit from the debt transfer. However, when capital mobility is low enough, country D can experience a decrease in income, as presented in Proposition 2. The difference observed between the two cases comes from the fact that when capital mobility is not perfect, country D experiences a crowding-out effect, which is not compensated by the crowding-in effect in country F. More precisely, an important question is to know how the increase of debt in country D is financed. If there is perfect mobility, the increase of b_D is financed with the over-saving of country F. Since the global amount of public debt is constant, there is no crowding-out effect. In contrast, as we have seen, if there is no mobility, an increase of b_D is not financed by external funds, which creates a crowding-out effect on capital of country D. More generally, a lower mobility of asset reduces this possibility of external funding of the increase of public debt b_D and reinforces the crowding-out effect of debt on capital in country D.

5 | CONCLUDING REMARKS

We examine in this paper the interplay between public debt and global environment. In a context of low interest rate, redefining debt policies and then examining their effects for environmental engagement are important. Indeed, low interest rate goes with the absence of fiscal costs but, at the same time, public debt can be costly as it can reduce capital accumulation. In an international context, the existence of this cost crucially depends on how the overall debt level evolves and how capital markets are integrated. In this paper, we question the effect of debt transfer in favor of low-income countries, the overall debt level remaining unchanged. We study the effects on both GDP and the environment when capital mobility is perfect or not.

When capital is perfectly mobile between countries, such a policy is not accompanied by negative crowding-out effect and it makes possible to increase GDP in both countries. As public spending for the environment goes up with country's income and is sufficiently efficient, the environmental quality increases as well. As the high-income economy is more patient, this scenario can emerge when the interest rate is sufficiency low. In that case, the debt transfer relaxes the fiscal pressure in high income country and global capital goes up. At the same time, the policy reduces the debt burden for the recipient country and hence it can increase the welfare of both economies. If the mobility of capital is imperfect, the increase in debt in high income countries goes with a fall in capital accumulation. Environmental quality can still improve, meaning that the main difference with perfect mobility mainly concerns the real side of the economy. The acceptability of the implementation of a debt relief could therefore depend on the degree of international openness. However, whatever the mobility of assets, debt relief could be welfare improving when environmental preferences are high enough.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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APPENDIX A

A.1 | Proof of Proposition 1

Differentiating Equation (16) at the stable steady state k_h, we get

$$\frac{dk_h}{db}\left[1+\left(\frac{A_F}{A_D}\right)^{\frac{1}{1-\alpha}}-G'(k_h)\right]=\frac{1+\beta_F\alpha A_D k_h^{\alpha-1}}{1+\beta_F}-\frac{1+\beta_D\alpha A_D k_h^{\alpha-1}}{1+\beta_D}. \tag{A1}$$

Note that $\frac{1+\beta_i\alpha A_D k_h^{\alpha-1}}{1+\beta_i}$ is increasing in β_i if and only if $R_h \equiv \alpha A_D k_h^{\alpha-1} > 1$ and decreasing if and only if $R_h < 1$. We deduce that

- $dk_h/db < 0$ if $R_h > 1$;
- $dk_h/db > 0$ if $R_h < 1$.

Using Equation (17) and Assumption 2, when debt relief increases (decreases) capital, it also improves (reduces) environmental quality.

A.2 | Proof of Corollary 2

Let

$$\widetilde{V}_{ih}=(1+\beta_i)\ln(w_{ih}-\tau_{ih})+\beta_i\ln(R_h). \tag{A2}$$

The welfare in a country i increases for all values of δ_i if following an increase of b_D and a decrease of b_F such that $db_D=-db_F=db>0$, $\widetilde{V}_{ih}$ raises. Using (2), (3), and (9), Equation (A2) writes:

$$\widetilde{V}_{ih}=(1+\beta_i)\ln\left[(1-\alpha-g_i)A_i k_i^{\alpha}+\left(1-\alpha A_i k_i^{\alpha-1}\right)b_i\right]+\beta_i\ln\alpha A_i k_i^{\alpha-1}. \tag{A3}$$

Differentiating this equation with respect to debt for country D and F, we get

$$\begin{aligned}\frac{d\widetilde{V}_{Dh}}{db}=&\frac{(1+\beta_D)(1-R_h)}{(1-\alpha-g_D)A_D k_D^{\alpha}+(1-R_h)b_D}\\&+\frac{[(1-\alpha-g_D)R_h(1-\beta_D(1-2\alpha)/\alpha)+(1-\alpha)(b_D/k_D)(R_h-\beta_D(1-2R_h))]dk_D/db}{(1-\alpha-g_D)A_D k_D^{\alpha}+(1-R_h)b_D},\end{aligned} \tag{A4}$$

$$\begin{aligned}\frac{d\widetilde{V}_{Fh}}{db}=&-\frac{(1+\beta_F)(1-R_h)}{(1-\alpha-g_F)A_F k_F^{\alpha}+(1-R_h)b_F}\\&+\frac{[(1-\alpha-g_F)R_h(1-\beta_F(1-2\alpha)/\alpha)+(1-\alpha)(b_F/k_F)(R_h-\beta_F(1-2R_h))]dk_F/db}{(1-\alpha-g_F)A_F k_F^{\alpha}+(1-R_h)b_F},\end{aligned} \tag{A5}$$

where R_h, k_F, and k_D are the values of R_{it}, k_{Ft}, and k_{Dt} evaluated at the steady state (k_h, E_h). Under Corollary 1, we have $dk_D/db > 0$ and $dk_F/db > 0$. Moreover, $\alpha \geqslant 1/3$ implies $\beta_i < 1 \leqslant \alpha/(1-2\alpha)$ and $R_h \geqslant 1/3$ implies $\beta_i < 1 \leqslant R_h/(1-2R_h)$.

We deduce that $d\widetilde{V}_{Dh}/db > 0$ which means that the welfare increases for country D, whereas the sign of $d\widetilde{V}_{Fh}/db$ is not clear-cut. It is positive if debt level in country F, b_F, is sufficiently high. Otherwise, as $dE_h/db > 0$, the welfare increases in country F if the weight in the utility associated with environmental quality δ_F is high enough.

A.3 | Proof of Proposition 2

Let $\widehat{k}_{F2}$ be a steady state of $k_{Ft+1} = G_F(k_{Ft})$ such that $G_F(k_{Ft})$ is tangent to the 45° line in the plane (k_{Ft}, k_{Ft+1}). Such an equilibrium exists if we could find $\widehat{k}_{F2}$ and $\widehat{b}_F$ solving $G_F(\widehat{k}_{F2}) = \widehat{k}_{F2}$ and $G_F'(\widehat{k}_{F2}) = 1$. Using (21), we get

$$\widehat{k}_{F2} = \frac{\beta_F}{1+\beta_F}(1-\alpha-g_F)A_F\widehat{k}_{F2}^{\alpha} - \frac{\widehat{b}_F\beta_F}{1+\beta_F}\alpha A_F\widehat{k}_{F2}^{\alpha-1} - \frac{\widehat{b}_F}{1+\beta_F}, \tag{A6}$$

$$\alpha\frac{\beta_F}{1+\beta_F}(1-\alpha-g_F)A_F\widehat{k}_{F2}^{\alpha-1} + (1-\alpha)\frac{\widehat{b}_F\beta_F}{1+\beta_F}\alpha A_F\widehat{k}_{F2}^{\alpha-2} = 1. \tag{A7}$$

Multiplying the second equation by $\widehat{k}_{F2}$ and substituting in the first one, we get

$$A_F\widehat{k}_{F2}^{\alpha-1} = \frac{1+\beta_F}{\beta_F(1-\alpha-g_F)}\left(\frac{1-\alpha}{1+\beta_F}\frac{\widehat{b}_F}{\widehat{k}_{F2}} + 2 - \alpha\right), \tag{A8}$$

whereas Equation (A7) may rewrite

$$A_F\widehat{k}_{F2}^{\alpha-1}\left[\alpha\frac{\beta_F}{1+\beta_F}(1-\alpha-g_F) + (1-\alpha)\frac{\beta_F}{1+\beta_F}\alpha\frac{\widehat{b}_F}{\widehat{k}_{F2}}\right] = 1. \tag{A9}$$

Combining these last two equations, we get

$$\frac{1+\beta_F}{\beta_F(1-\alpha-g_F)}\left(\frac{1-\alpha}{1+\beta_F}\frac{\widehat{b}_F}{\widehat{k}_{F2}} + 2 - \alpha\right)\left[\alpha\frac{\beta_F}{1+\beta_F}(1-\alpha-g_F) + (1-\alpha)\frac{\beta_F}{1+\beta_F}\alpha\frac{\widehat{b}_F}{\widehat{k}_{F2}}\right] = 1. \tag{A10}$$

The left-hand side of this equation is a decreasing function of $\widehat{k}_{F2}/\widehat{b}_F$, which tends to $+\infty$ when $\widehat{k}_{F2}/\widehat{b}_F$ tends to 0 and tends to $\alpha(2-\alpha)$ when $\widehat{k}_{F2}/\widehat{b}_F$ tends to $+\infty$. Therefore, $\alpha(2-\alpha) < 1$ ensures the existence and uniqueness of a solution $\widehat{k}_{F2}/\widehat{b}_F$. Given such a solution, Equation (A9) gives a unique $\widehat{k}_{F2}$. The existence and uniqueness of $\widehat{b}_F$ of course follow.

Considering the concavity of $G_F(\widehat{k}_{F2})$, for b_F slightly smaller than $\widehat{b}_F$, there exists a steady state k_{F2} higher than and close to $\widehat{k}_{F2}$ with $G_F'(k_{F2})$ smaller but close to 1. In this case, Equation (24) allows to deduce that $dE_2/db > 0$, whereas we already know from (22) that $dk_{D2}/db < 0$ and $dk_{F2}/db > 0$.