La spatialisation dans les modèles micro-économiques d'offre agricole pour l'analyse des politiques environnementales : application aux cas de la biodiversité et de la biomasse-énergie

Laure Bamière

ParisTech
INSTITUT DES SCIENCES ET TECHNOLOGIES
PARIS INSTITUTE OF TECHNOLOGY

AgroParisTech
INSTITUT DES SCIENCES ET INDUSTRIES DU VIVANT ET DE L'ENVIRONNEMENT
PARIS INSTITUTE OF TECHNOLOGY FOR LIFE, FOOD AND ENVIRONMENTAL SCIENCES

Ecole Doctorale ABIES
Agriculture Agriculture Alimentation Food Biologie Biology Environnement Environment Santé Health

Doctorat ParisTech

THÈSE

pour obtenir le grade de docteur délivré par

L'Institut des Sciences et Industries du Vivant et de l'Environnement

(AgroParisTech)

Spécialité : Economie

présentée et soutenue publiquement par

Laure BAMIERE

le 19 Décembre 2013

La spatialisation dans les modèles micro-économiques d'offre agricole pour l'analyse des politiques environnementales :

Application aux cas de la biodiversité et de la biomasse-énergie

Directeur de thèse : **Florence JACQUET**

Jury

Mme Sophie THOYER, Professeur, UMR LAMETA, Supagro Montpellier	Rapporteur
M. Frédéric LANTZ, Professeur, Centre Economie et Gestion, IFP School	Rapporteur
M. Jean-Philippe BOUSSEMART, Professeur, Université Lille3	Examinateur
Mme Chantal LE MOUEL, Directeur de Recherche, UMR SMART, INRA	Examinateur
M. Jean-Christophe BUREAU, Professeur, UMR Economie Publique, AgroParisTech	Président
Mme Florence JACQUET, Directeur de Recherche, UMR MOISA, INRA	Directeur de thèse

INRA
UMR 210 Economie Publique
Avenue Lucien Brétignières, BP01, 78850 Thiverval-Grignon

La spatialisation dans les modèles micro-économiques d'offre agricole pour l'analyse des politiques environnementales : application aux cas de la biodiversité et de la biomasse-énergie

Laure Bamière *

19 Décembre 2013

*UMR Economie Publique, INRA-AgroParisTech, BP01, 78850 Thiverval-Grignon, France.

L’école doctorale ABIES-AGROPARISTECH n’entend donner aucune approbation ni improbation aux opinions émises dans les thèses ; ces opinions doivent être considérées comme propres à leurs auteurs.

Remerciements

Je tiens à remercier Florence Jacquet pour avoir accepté de diriger ma thèse et m'avoir incitée à prendre du recul sur mon travail d'ingénieur et de modélisateur.

Je remercie sincèrement l'ensemble des membres du jury qui m'ont fait l'honneur d'évaluer mon travail et m'ont fourni des pistes de reflexion et d'amélioration pour les années à venir. Je remercie Sophie Thoyer et Frédéric Lantz pour l'intérêt qu'ils ont porté à mes travaux en acceptant d'être rapporteurs. Je remercie également Chantal Le Mouël, Jean-Philippe Boussemart et Jean-Christophe Bureau d'avoir accepté de participer à ce jury en tant qu'examinateurs.

Je remercie chaleureusement toutes les personnes qui m'ont soutenue et supportée au cours de ces six années, et m'ont permis d'aller jusqu'au bout de ce projet de thèse :

Jean-Christophe Bureau pour m'avoir encouragée, en tant que directeur d'unité, à faire une thèse sur travaux.

Pierre-Alain Jayet auprès de qui j'ai fait mes armes en modélisation et en programmation mathématique, ainsi que Jean-Claude Souris pour m'avoir mis le pied à l'étrier des projets qui sont à l'origine des quatre articles de cette thèse.

Mes co-auteurs et les les partenaires des projets PRAITERRE et ECOBIOM, avec qui j'ai eu des collaborations enrichissantes.

Mes collègues et ex-collègues, tout particulièrement Raja Chakir, Maïa David, Vincent Martinet, Petr Havlik, Stéphane De Cara et Estelle Gozlan, qui par nos nombreuses discussions, leurs conseils ou relectures, m'ont permis de progresser et m'ont beaucoup appris. Mais aussi Loïc Guindé et Guy Millet, pour nos échanges sur les modèles, leur validation et leurs résultats.

Les doctorants et post-doctorants du labo, toujours prêts à partager leurs connaissances techniques et informatiques entre autres en LateX et R.

Toute l'équipe d'appui à la recherche de l'UMR Economie Publique, notamment pour son soutien logistique et dans la recherche de références bibliographiques.

Mon mari et mes parents, pour leur soutien sans faille au quotidien et sur le long terme, et sans qui je n’aurais pu dégager le temps nécessaire pour mener à bien ce projet.

A very special thank to Suzette Tanis-Plant for, indeed, her thorough editorial advice in English and our fruitful disussions, that helped me sort out my ideas and also greatly improved my articles. But most of all, she helped me "giving birth" to this PhD thesis by her constant support and encouragement at all stages.

Enfin je tiens également à remercier l’équipe de l’école docorale ABIES pour sa disponibilité et sa gentillesse.

Table des matières

Introduction générale **1**

I Offre de biomasse lignocellulosique à des fins énergétiques **11**

1 A spatially explicit model to analyse the regional supply of ligno-cellulosic biomass **13**

1.1 Introduction 13
1.2 Methodology 18
1.3 Case study 26
1.4 Results 37
1.5 Conclusion and Discussion 51
1.6 Perspectives 53
1.A Appendix Model equations 54
1.B Appendix Case study 59
1.C Appendix Results 72

2 Stochastic viability of second generation biofuel chains: Micro-economic spatial modeling in France **73**

2.1 Introduction 74
2.2 Methodology 76
2.3 Case study 83
2.4 Results 87
2.5 Discussion and conclusion 93

II Conservation de la biodiversité en milieu agricole **96**

3 Farming system modelling for agri-environmental policy design: The case of a spatially non-aggregated allocation of conservation measures **98**

3.1 Introduction 99
3.2 Methodology 102
3.3 Case Study 106
3.4 Simulations and Results 113
3.5 Conclusion 118
3.A Appendix. Ripley K and L Functions 120

4 Agri-environmental policies for biodiversity when the spatial pattern of the reserve matters 123

4.1 Introduction 123
4.2 The mathematical programming model 127
4.3 A comparison of policy instruments 130
4.4 The auction scheme 131
4.5 The agglomeration malus 135
4.6 Summary and discussion 139

Conclusion générale 141

Bibliographie 146

Introduction générale

Problématique

La dimension spatiale est importante pour un certain nombre de politiques publiques portant sur l'environnement. C'est le cas par exemple de la Directive Cadre sur l'Eau (2000/60/CE), qui a pour objectif la préservation et la restauration de l'état des eaux superficielles et souterraines. En effet, pour améliorer la qualité des eaux, il est important de cibler les aires de captage qui approvisionnent les nappes phréatiques contaminées. Ainsi la Directive Nitrates (91/676/CEE), qui a plus particulièrement pour objectif de réduire la pollution des eaux par les nitrates d'origine agricole, définit des zones dites vulnérables sur lesquelles sont imposées certaines pratiques agricoles. La dimension spatiale est aussi importante dans le cas des politiques concernant la protection de la biodiversité ou la promotion de sources d'énergie renouvelables. Ce sont ces politiques auxquelles nous nous sommes intéressés.

Au niveau européen, des politiques de protection de la biodiversité ont déjà été mises en place. Par exemple, la conservation des oiseaux sauvages et celle des habitats naturels, de la faune et de la flore sauvages, reposent principalement sur les directives " Oiseaux " (79/409/CEE et 2009/147/CE) et "Habitat" (92/43/CEE). Elles ont abouti à la mise en place du réseau Natura 2000, qui regroupe les zones de protection spéciales (ZPS) et les zones spéciales de conservation (ZSC). Ces zones font l'objet de mesures de conservation spécifiques, adaptées au contexte locale. Il existe notamment depuis quelques années des Mesures Agro-Environnementales Territorialisées (MAEt), financées dans le cadre du " 2ème pilier " de la Politique Agricole Commune (PAC), qui ciblent les zones prioritaires " à enjeu eau " (Kuhfuss et al., 2012) mais aussi "à enjeu biodiversité". Les agro-écosystèmes abritent par exemple la moitié des espèces d'oiseaux se reproduisant sur le territoire européen, dont beaucoup sont menacées. La biodiversité agricole dépend de l'existence d'une mosaïque paysagère complexe et diversifiée, ainsi que de l'existence de pratiques extensives, notamment concernant la gestion des prairies (Le Roux et al., 2008). L'intensification des pratiques et l'homogénéisation du paysage agricole depuis les années 1950 ont entrainé un déclin de la biodiversité spécifique au milieu agricole. Il y a globalement deux approches pour conserver la biodiversité : mettre des terres en réserve et les préserver de toute activité humaine, connu sous le terme "land sparing", ou trouver un moyen de faire cohabiter espèces menacées et activités humaines, connu sous le terme "land sharing". Les MAEt "biodiversité" sont typiquement un exemple de "land sharing".

Toutefois, concevoir une mesure spécifique à un territoire n'est pas nécessairement suffisant. L'effet d'une mesure de conservation ne dépend pas seulement de la mise en œuvre de pratiques respectueuses de la faune ou de la flore locales, sur un nombre de parcelles données. Leur configuration spatiale joue aussi un rôle. Ainsi, à surface totale équivalente, avoir des sites fragmentés, agrégés, formant un corridor ou des pas japonais n'aura pas le même impact selon l'espèce visée, sa mobilité ou sa capacité de dispersion. Par ailleurs, la mosaïque paysagère agricole est importante pour d'autres problématiques environnementales telles que la lutte contre l'érosion, la lutte contre les insectes ravageurs et la réduction des pesticides, ou le lessivage des nitrates.

Un autre exemple où la prise en compte de la dimension spatiale est importante est la production de biomasse énergie. L'Union Européenne promeut le recours aux sources d'énergie renouvelables, dont la biomasse agricole et forestière, à la fois pour des raisons d'indépendance énergétique, de sécurité de l'approvisionnement et de réduction des émissions de gaz à effet de serre. La directive sur les Energies renouvelables (2009-28-CE) insiste sur le fait que cette production d'énergie renouvelable doit respecter des critères de durabilité économique, environnementale et sociale. La durabilité économique implique que la production d'énergie renouvelable soit compétitive par rapport aux énergies auxquelles elle se substitue, du moins à terme quand les technologies de production à grande échelle seront optimisées. En l'occurrence pour la biomasse agricole et forestière, étudier la durabilité économique implique de savoir quel type de biomasse sera disponible à quel endroit, en quelle quantité et à quel coût. La durabilité environnementale implique que la production d'énergie renouvelable ne cause pas plus de problèmes qu'elle n'en résout. Par exemple, la directive précise que les biocarburants et bioliquides doivent permettre de diminuer les émissions de GES d'au moins 35% (60% à partir de 2018) par rapport aux énergies fossiles auxquelles ils se substituent. Pour effectuer ce bilan il convient de tenir compte des changements directs et indirects d'affectation des sols. Notamment leur production ne doit pas s'effectuer sur les sols à fort stock de carbone, si cela génère des émissions de GES qui viennent annuler l'atténuation escomptée par l'usage des biocarburants. Leur production ne doit pas non plus se faire au détriment de terres à forte richesse en biodiversité, des forêts primaires et des prairies naturelles, et si possible recourir de préférence aux terres dégradées et restaurées plutôt qu'aux terres agricoles de bonne qualité. Pour évaluer la durabilité environnementale de la filière de biomasse énergie, il convient donc notamment de savoir quel type de biomasse sera produit, à quel endroit et selon quelles pratiques (ex : intensité d'utilisation des intrants, irrigation ou non). La localisation respective des lieux de production, de transformation et de consommation a aussi un impact sur la compétitivité et sur l'environnement via les transports.

Dans ce travail de recherche, nous nous intéressons plus particulièrement à la conservation de la biodiversité en milieu agricole et à la production de biomasse-énergie par le secteur agricole. L'agriculture a certaines spécificités. Les décisions de production sont prises par un grand nombre d'agents privés, sans forcément tenir compte spontanément des externalités environnementales. En général, les agriculteurs maximisent leurs profits en tenant compte de contraintes techniques et réglementaires. Par exemple, le type de biomasse qui est économiquement le plus intéressant pour un agriculteur n'est pas nécessairement ce qui est le mieux pour l'environnement. D'autre part, il existe à la fois une grande diversité de systèmes d'exploitation, tant sur le type de production (ex : céréaliculture, polyculture-élevage.) que sur son intensité (ex : élevage bovin extensif vs. élevage hors sol), mais aussi une hétérogénéité des conditions de production (terre de différentes qualités, conditions climatiques variées). Le fait que les décisions de production soient prises par un grand nombre d'agents économiques privés joue sur la conception et la mise en œuvre des politiques publiques. Les terres agricoles appartiennent à des agriculteurs, qui ne prennent pas leurs décisions de manière concertée. Il faut donc trouver un moyen de les inciter à mettre en œuvre des pratiques respectueuses de l'environnement. Et que celles-ci s'agencent dans l'espace de manière harmonieuse et efficace par rapport à l'objectif visé. Le fait qu'il existe une grande diversité de systèmes d'exploitation et de conditions de production est, quant à lui, à l'origine d'hétérogénéités dans les coûts de production et les coûts de mise en œuvre des politiques publiques, entre les agriculteurs et entre les régions. Par ailleurs, un même choix technique ou de production n'aura pas nécessairement les mêmes conséquences selon le type d'exploitation ou le contexte pédo-climatique. Ces hétérogénéités jouent sur l'efficacité et le coût de mise en œuvre, pour le régulateur, des différents instruments de politique publique à sa disposition. Ces spécificités du secteur agricole soulignent l'importance de la prise en compte des décisions des exploitants et des caractéristiques de leurs exploitations (système de production et contexte pédoclimatique).

Cette thèse aborde la question générale de l'élaboration de politiques publiques permettant une répartition spatiale des activités agricoles qui soit efficace d'un point de vue environnemental, dans les domaines de la protection de la biodiversité et de la production de biomasse-énergie. La conception et l'évaluation de telles politiques nécessitent des modèles capables de prendre en compte à la fois les aspects spatiaux, la prise de décision au niveau des exploitations agricoles et une modélisation fine des systèmes d'exploitation. Dans les articles qui constituent cette thèse, nous avons plus précisément abordé les aspects méthodologiques du développement de tels modèles.

Cadre conceptuel

Compte tenu de la problématique de nos travaux, c'est-à-dire la conception de politiques agro-environnementales, nous nous trouvons confrontés à plusieurs problèmes qui sont : l'asymétrie d'information, l'hétérogénéité de coût entre les agents et l'hétérogénéité spatiale.

L'asymétrie d'information entre le régulateur publique et les agriculteurs provient du fait que le régulateur ne connaît pas le coût de mise en conformité de chaque agriculteur, qui est une information privée. Si le régulateur disposait de cette information, il pourrait proposer aux agriculteurs le montant qui compenserait exactement leur coût de mise en œuvre de la mesure. Ainsi, à objectif environnemental donné, le coût budgétaire de la politique serait minimisé pour l'Etat. Malheureusement, acquérir cette information pour tous les agents, si toutefois c'était possible, coûterait très cher, compte-tenu du grand nombre d'agents et de l'hétérogénéité de leurs coûts, et rendrait prohibitif le coût total de la mesure agro-environnementale. Par ailleurs, les agriculteurs n'ont pas intérêt à révéler leur coût réel, mais plutôt des coûts plus élevés, pour augmenter leur paiement compensatoire. Il y a donc un problème de sélection adverse. Actuellement en Europe, les mesures agro-environnementales font généralement l'objet d'une subvention uniforme par hectare contractualisé. Les agriculteurs ayant un coût marginal de mise en oeuvre de la mesure inférieur à la subvention sont donc surcompensés, c'est ce qu'on appelle la rente d'information. En cas d'information imparfaite, et faute de pouvoir appliquer une solution de premier rang, le régulateur essaie de recourir à un instrument incitatif de deuxième rang qui soit "coût-efficace". C'est-à-dire un instrument qui permette d'atteindre un objectif environnemental donné en limitant les surcompensations. Parmi les instruments à disposition du régulateur, on trouve par exemple les contrats différenciés (Wu and Babcock, 1996), les systèmes d'enchères (Latacz-Lohmann and Van der Hamsvoort, 1998, 1997; Glebe, 2008), les taxes et les subventions (uniformes ou différentiées).

La question du choix d'un instrument de politique adapté en présence d'hétérogénéité spatiale, c'est-à-dire quand l'impact environnemental dépend de la localisation des activités et des pratiques agricoles, a déjà été abordée dans le domaine de la régulation des pollutions diffuses d'origine agricole de type pollution des eaux par les nitrates (voir Bourgeois, 2012 pour une revue). Ainsi quand les cultures ont des fonctions d'émission différentes pour un même niveau de fertilisation, une taxe sur l'intrant différenciée par culture est en théorie préférable à une taxe uniforme (Helfand et al., 2003). Et une forte variabilité des coûts marginaux de réduction de la pollution, due par exemple à l'hétérogénéité des terres, tend à favoriser une taxe uniforme plutôt qu'une norme uniforme sur les intrants (Wu and Babcock, 2001).

La dimension spatiale a aussi été abordée dans la littérature économique via la prise en compte de la distance et des coûts de transport dans les choix de localisation des entreprises et des ménages, comme c'est le cas en économie géographique (voir Thisse, 1997 pour un historique de la prise en compte de l'espace en économie). L'économie géographique explique la concentration des activités par des interactions entre plusieurs facteurs qui sont : la présence rendements d'échelle croissants et de coût de transports, et la mobilité des facteurs de production (Fujita et al., 2001). Von Thünen a été un des précurseurs en 1826 en étudiant la localisation des activités agricoles autour d'une ville isolée. Il a fait l'hypothèse que les cultures avaient des rendements et des coûts de transport différents, et qu'elles pouvaient être produites de manière plus ou moins intensive. Il a ensuite déterminé i) l'allocation des terres autour de la ville permettant de minimiser le coût de production et de transport des denrées alimentaires pour satisfaire la demande (fixée) de la ville ; et ii) l'allocation effective des terres si on laisse faire la compétition entre fermiers et propriétaires terriens. Il montre que l'allocation des terres est la même dans les deux cas et que les cultures sont réparties en anneaux concentriques autour de la ville : d'abord les cultures maraîchères, puis les céréales et enfin l'élevage extensif en extrême périphérie. La compétition entre agriculteurs génère un gradient de rente foncière qui décroît en s'éloignant de la ville. Les agriculteurs doivent donc arbitrer entre un coût de la terre plus élevé ou des coûts de transports plus élevés.

En somme, étant données les problématiques de la biodiversité et de la production biomasse-énergie dans le secteur agricole, nous nous situons dans le cadre de la conception de politiques publiques en présence d'asymétrie d'information, de sélection adverse et d'hétérogénéité spatiale. Dans le cas précis de l'offre de biomasse-énergie, nous nous rapprochons de la conception de la dimension spatiale par l'économie géographique. C'est-à-dire que nous intégrons les distances et les coûts de transport dans les choix de localisation de la production.

Cadre méthodologique

Dans le cadre de cette thèse, nous nous sommes concentrés sur le développement de modèles pour concevoir et évaluer des politiques publiques permettant une répartition spatiale des activités agricoles qui soit efficace d'un point de vue environnemental. Ces modèles doivent être capables de prendre en compte à la fois les aspects spatiaux, la prise de décision au niveau des exploitations agricoles et une modélisation fine des systèmes d'exploitation. Pour simuler l'allocation des usages de sols par les agriculteurs, nous avons le choix entre deux approches : les modèles économétriques ou les modèles de programmation mathématique. L'estimation des modèles économétriques est basée sur des séries de données observées dans le passé. Ils ne donc peuvent prédire que les usages des sols qui étaient dans leur estimation. Comme nous avions besoin d'introduire de nouvelles productions et de nouvelles pratiques, nous avons opté pour les modèles de programmation mathématique. Ils permettent de tenir compte explicitement des différentes techniques de production, c'est-à-dire du lien entre intrants, produits et impacts environnementaux (Flichman and Jacquet, 2003). Ils peuvent être alimentés en données techniques par des bases de données de référence, à dire d'expert ou par des modèles agronomiques ou bio-techniques. On peut donc leur ajouter de nouvelles activités et simuler les impacts de changements de politiques sur l'offre agricole et l'environnement. L'usage de modèles d'exploitations fondés sur la programmation mathématique permet d'évaluer, de manière endogène, le coût d'opportunité de changements de pratiques ou d'usages des sols, ce en tenant compte des contraintes et ajustements possibles au sein des exploitations (ex : contraintes rotationnelles, rations du troupeau). Pour toutes ces raisons, les modèles d'exploitations et de programmation mathématique nous semblaient plus adaptés à nos besoins.

Ces modèles sont traditionnellement utilisés dans l'évaluation et l'aide à la conception des politiques publiques dans le secteur agricole. C'est le cas par exemple pour la politique agricole commune et ses réformes (ex : Britz et al., 2012; Galko and Jayet, 2011), pour les politiques agro-environnementales (Falconer and Hodge, 2001; van Wenum et al., 2004; Ekman, 2005; Havlik et al., 2005; Wossink et al., 1992; Jacquet et al., 2011; Mouysset et al., 2011), ou encore les politiques énergétiques promouvant les biocarburants (ex : Rozakis and Sourie, 2005; Sourie et al., 2005; Guindé et al., 2008; Louhichi and Valin, 2012). Les modèles utilisés sont généralement basés sur la simulation du comportement d'exploitations agricoles "types", en utilisant par exemple les exploitations de l'échantillon du Réseau d'Information Comptable Agricole ([1]). Toutefois, ces modèles ne prennent

[1]Ces exploitations types sont chacune représentative d'un sous-ensemble d'exploitations réelles à

généralement pas en compte la dimension spatiale dans les choix de production.

Il existe par ailleurs des modèles qui prennent en compte la dimension spatiale (de différentes façons), mais qui n'intègrent pas ou très mal les aspects économiques importants tels que les coûts, la compétition pour l'usage des sols, ou la prise de décision individuelle au niveau de l'exploitation agricole. Par exemple, dans le domaine de la conservation de la biodiversité, il existe des modèles de "*reserve design*". Ils sélectionnent des sites à mettre en réserve en tenant compte de la configuration spatiale de l'ensemble, de manière à atteindre un objectif de conservation donné, éventuellement de manière coût-efficace (voir Williams et al., 2005, pour une revue, et Wossink et al., 1999, pour un exemple en milieu agricole). D'autres modèles tiennent explicitement compte de la configuration spatiale du paysage agricole, pour analyser les effets de mesures incitatives de protection de la biodiversité (ex : Drechsler et al., 2007, 2010; Hartig and Drechsler, 2009; Johst et al., 2002; Lewis and Plantinga, 2007; Lewis et al., 2009; Wätzold and Drechsler, 2005; Wätzold et al., 2008). Ces études considèrent toutes des coûts exogènes pour les changements de pratique ou d'usage des sols sur les parcelles agricoles. Elles ne tiennent pas compte de la prise de décision au niveau des exploitations. Dans le domaine de l'offre de biomasse-énergie, certains modèles évaluent le gisement potentiel de biomasse et sa localisation à un grain fin en tenant compte du contexte agropédoclimatique. Soit ils ne tiennent pas compte de la compétition pour l'usage des sols entre les activités agricoles (ex : Fischer et al., 2010; de Wit and Faaij, 2010), soit ils ne l'autorisent que sur une fraction des terres en comparant des marges brutes exogènes (ex : van der Hilst et al., 2010; Ugarte and Ray, 2000; Ballarin et al., 2011). Dans les deux cas on ne dispose pas du coût d'opportunité de la biomasse pour une demande donnée. D'autres modèles cherchent à optimiser la localisation et/ou la taille des unités de conversion dans un bassin d'approvisionnement, en tenant compte des coûts de transport de la biomasse vers l'usine, voire même du carburant jusqu'aux lieux de consommation (ex : Bryan et al., 2008; Leduc et al., 2009; Tittmann et al., 2010; Kocoloski et al., 2011; Schmidt et al., 2010). Là encore, soit les coûts et les quantités de biomasse sont exogènes, soit ils ne tiennent pas compte de la compétition avec les autres commodités. Dans tous les exemples cités ci-dessus, il manque la modélisation du choix des agriculteurs.

L'objectif des travaux présentés dans cette thèse est donc de prendre en compte à la fois les aspects spatiaux et les décisions des exploitations agricoles dans les modèles de programmation mathématique, pour la conception et l'évaluation des politiques agro-environnementales.

l'échelle d'une région, via un coefficient de pondération. Elles couvrent globalement l'ensemble des systèmes d'exploitation.

Nous avons pris en compte les aspects spatiaux à différents niveaux . Pour commencer, nous avons tenu compte du contexte agro-pédo-climatique, c'est-à-dire nous avons distingué dans les modèles des zones géographiques ayant des caractéristiques différentes du point de vue du climat, de la qualité des sols, voire des pratiques agricoles. Ce contexte détermine les cultures possibles, les potentialités de rendement, les pratiques culturales et les niveaux d'intrants nécessaires. Une même pratique culturale n'ayant pas forcément les mêmes conséquences en fonction du contexte pédoclimatique, tout ceci influence à son tour les impacts environnementaux liés à la production agricole. D'autre part, nous avons cartographié les activités agricoles avec un grain plus ou moins fin. On peut ainsi tenir compte des distances entre activités agricoles ou entre lieux de production et de consommation. Cela permet d'intégrer les coûts de transport dans les décisions de production et d'approvisionnement. Nous avons aussi calculé des indicateurs spatiaux tenant compte de la taille et/ou de l'agencement des activités dans l'espace. Cet agencement a souvent un impact sur les externalités environnementales : concentration éventuelle des pollutions, ouverture/fermeture du paysage, création de trames vertes pour la biodiversité ou, au contraire, destruction d'habitats semi-naturels et extinction d'espèces. Ces indicateurs spatiaux peuvent être calculés à partir des sorties du modèle, c'est-à-dire à partir de l'allocation des terres aux différentes activités agricoles, ou intégrés sous forme de contrainte dans le modèle si c'est techniquement faisable. Enfin nous avons représenté plusieurs niveaux spatiaux qui intéragissent tout en ayant des contraintes propres, comme c'est le cas pour la parcelle, l'exploitation et le "paysage".

Plan de la thèse

Cette thèse est composée de quatre articles, regroupés en deux parties correspondant chacune à une thématique : l'offre de biomasse lignocellulosique à des fins énergétiques d'une part, et la conservation d'une espèces menacée en milieu agricole, d'autre part.

Dans la première partie de la thèse, nous nous plaçons en amont de la conception d'une politique publique. En effet, pour répondre aux objectifs de la Directive Européenne sur les Energies Renouvelables, les secteurs agricoles et forestiers doivent être en mesure de produire de manière durable, d'un point de vue économique et environnemental, de la biomasse lignocellulosique. Deux questions se posent alors : i) une telle production est-elle possible sans intervention ? ; ii) si non, quelle politique mettre en œuvre pour que la production de biomasse-énergie satisfasse les critères de durabilité ? Pour répondre à ces questions il faut en premier lieu être capable d'analyser l'offre de biomasse et les impacts de sa production, face à une demande accrue. Dans le chapitre 1, nous développons un modèle régional d'offre de biomasse agricole et forestière, spatialement explicite et à maille cantonale. Les aspects spatiaux y sont abordés à la fois par la prise en compte du contexte agro-pédo-climatique, de deux niveaux spatiaux (l'exploitation "cantonale" et la région), des distances et coûts de transport entre les lieux de production et d'utilisation de la biomasse. Le modèle est ensuite appliqué à la région Champagne-Ardenne afin i) de générer des courbes d'offre de biomasse en fonction du contexte économique, ii) d'évaluer des impacts environnementaux associés, iii) d'optimiser simultanément la localisation de la production de biomasse et d'une usine de bioénergie. Nous remettons en cause quelques idées communément admises sur la biomasse-énergie en France. Nous mettons notamment en évidence que les cultures énergétiques sont produites sur les terres les plus fertiles et que les rémanents forestiers restent non-exploités. Le chapitre 2 est une extension du chapitre précédent. Nous étudions la viabilité technique et économique d'une usine d'éthanol de 2ème génération au cours du temps, dans un contexte économique incertain. Nous calculons la probabilité de viabilité de différentes stratégies d'approvisionnement en biomasse. Les contraintes de demande et les scénarios de prix au cours du temps des commodités agricoles sont introduits dans le modèle d'offre de biomasse, qui en retour fournit les coûts d'approvisionnement et calcule la probabilité de viabilité.

Dans la deuxième partie de la thèse, nous nous penchons sur la conception d'une mesure agro-environnementale coût-efficace. Celle-ci a pour objectif la préservation de l'habitat naturel de l'Outarde Canepetière, une espèce emblématique menacée. Elle nécessite une répartition spatiale non-agrégée des parcelles contractualisées, à l'échelle d'un territoire. Pour analyser la conception et la mise en oeuvre d'une telle mesure, nous avons développé un modèle associant une représentation fine des systèmes d'exploitation à une approche spatialement explicite. Les aspects spatiaux y sont abordés par la prise en compte du contexte agro-pédo-climatique et de trois niveaux spatiaux (parcelle, exploitation et territoire), ainsi que par le calcul d'un indicateur spatial pertinent pour notre problème. Nous présentons ce modèle dans le chapitre 3. Nous l'utilisons dans un premier temps de manière "normative", pour étudier la localisation des parcelles contractualisées permettant de répondre aux objectifs de préservation de l'habitat à moindre coût. Dans un deuxième temps, nous l'utilisons pour étudier la capacité de différents types de subventions à générer suffisamment de parcelles contractualisées et réparties de manière adéquate, ce à moindre coût. Le modèle est appliqué à une zone stylisée représentative de la Plaine de Niort, un site Natura 2000. Nous montrons qu'à surface protégée égale, la configuration spatiale non-agrégée coûte plus cher car elle requiert une égale participation des céréaliers et des éleveurs. Elle peut être obtenue par un système de paiements dégressifs à deux niveaux, encourageant toutes les exploitations à contractualiser au moins une petite proportion de leurs parcelles. Le chapitre 4 est une extension du chapitre précédent, qui compare le coût et l'efficacité d'autres instruments incitatifs pour répondre à l'objectif de préservation. Ces instruments sont une subvention couplée à malus à l'agglomération et un système d'enchère. Nous montrons que l'enchère permet de réduire le coût total de la mesure par rapport à une subvention uniforme, en limitant la surcompensation des agriculteurs. La subvention couplée à un malus à l'agglomération est plus efficace que les autres instruments en terme de configuration spatiale, pour un coût équivalent à celui de la subvention uniforme.

Première partie

Offre de biomasse lignocellulosique à des fins énergétiques

La première partie de cette thèse fait suite à des travaux menés dans le cadre d'un projet de recherche interdisciplinaire, financé par l'Agence Nationale de la Recherche dans le cadre du Programme Nationale de Recherche sur les Bioénergies, le projet ECO-BIOM : « Une approche socio-ECOnomique et environnementale de l'offre de BIOMasse lignocellulosique » (ANR-05-PNRB-BIOE-18, 2005-2009). Ce projet était coordonné par Elisabeth LeNet, de la FCBA, et avait pour partenaires l'INRA (UMR Economie Publique et UMR Environnement Grandes Cultures), le GIE ARVALIS/ONIDOL, l'UCFF, l'ONF et le CNRS (GATE). Il avait pour objectif de proposer différents outils de détermination des conditions d'approvisionnement économiquement pérennes des unités de production de bioénergies, en biomasse agricole et forestière. Parmi ces outils figurait un modèle générique, spatialement explicite, d'offre de biomasse utilisable au niveau régional avec une maille cantonale.

Le chapitre 1 présente ce modèle et son application à la région Champagne-Ardenne. Il est issu d'un working paper présenté pour la première fois à Amsterdam en 2009 lors de la conférence annuelle de la European Association of Environmental and Resource Economists(EAERE). Le chapitre 2 utilise ce même modèle pour étudier la viabilité de différentes stratégies d'approvisionnement d'une unité de production d'éthanol de 2ème génération. Il est issu d'un working paper en collaboration avec Vincent Martinet et Christophe Gouel, présenté à Rome lors de la 18ème conférence annuelle de l'EAERE (2011), à Zürich lors du 13ème congrès de la European Association of Agricultural Economists (EAAE, 2011) et en cours de soumission.

Chapter 1

A spatially explicit model to analyse the regional supply of ligno-cellulosic biomass

1.1 Introduction

Throughout the world, the mitigation of greenhouse gas emissions is underway and the means to attain energy independence are under discussion. To this end, renewable sources of energy are being presented as alternatives to the finite supply of environmentally-problematic fossil fuels. To ensure progress in this direction, the European Union set mandatory targets in terms of the amount of energy produced from renewable sources. By 2020, that amount is to be 20% of the overall European Community's energy consumption and 10% of each Member State's energy consumption in the transportation sector alone (Parliament and the EU Council, DIRECTIVE2009-28-EC). Moreover, the European Commission laid stress on the importance of producing renewable energy sources on the local level so as to better secure the supply as well as to develop employment and rural opportunities. The commission also indicated that any production of an alternative source of energy needed to comply with economic, environmental, and social sustainability criteria [1]. According to Directive 2001/77/EC, "renewable energy sources" are defined as renewable non-fossil energy sources, ranging from wind, solar, geothermal, and hydropower to landfill gas, sewage treatment plant gas, biogases and biomass. The

[1]Environmental sustainability criteria imply, for instance, a decrease by at least 35% (60% from 2018 on) of GHG emissions compared to the fossil fuels to which they substitute, including GHG emissions due to direct and indirect land use change. Renewable energy sources production must not occur at the expense of high biodiversity value land, primary forest, natural grasslands, and good quality agricultural land.

Directive further defines "biomass" as the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste.

For numerous reasons, biomass is expected to play an important role in reaching EU targets. First and foremost, it is renewable. Secondly, it can be cultivated in all regions. It can also be converted into heat, electricity or biofuels as well as stored in huge quantities.

First generation biofuels, from oil and starch crops, have been heavily subsidized to compensate for a lack of competitivity compared to fossil fuels and to support their development. However, doubt soon shadowed the worthiness of such incentives given the externalities of the production of these biofuels (Scarlat and Dallemand, 2011; Searchinger et al., 2008; Zilberman et al., 2013). Competition with food crops results in indirect land-use change, questionable environmental benefits, and even a negative carbon balance. First generation biofuels were also accused of being responsible for the food price crisis. Lastly, first generation biofuels were found not to comply with sustainability criteria.

Now, the focus has shifted to lignocellulosic bioenergy, including second generation biofuels. In this case, bioenergy is produced by processing the whole plant, in particular its lignocellulose (the main component of plant cell walls). There exists a wide range of lignocellulosic feedstocks including crop residues (such as cereal straw and corn stover), dedicated annual crops (such as fiber sorghum and whole plant triticale), dedicated perennial crops (such as Miscanthus and Switchgrass), woody biomass produced on agricultural land (such as poplar or willow short rotation coppices), and forest biomass (such as roundwood and remnants). In addition, lignocellulosic bioenergy chains are expected to be more compatible with sustainability criteria. First of all, lignocellulosic biomass usually has higher energy content and yields than food crops for lower input levels. Secondly, it can be grown on marginal land. Thirdly, it is possible to use crop residues and forest biomass, including trunks and remnants (branchwood usually left on the ground after logging). A major question remains: while complying with sustainability criteria, to what extent can the agricultural and the forest sectors contribute to the production of lignocellulosic bioenergy at both global and regional scales?

This question has been tackled using various approaches in several studies (see Berndes et al., 2003, for a review of 17 studies at the global level; EEA, 2006; Ericsson and Nilsson, 2006; and Fischer et al., 2010 for an assessment of the overall EU biomass potential production). These studies showed that a large-scale biomass supply is technically feasible and that EU policy targets are technically achievable, even without harming the environment. They all conclude that agricultural and forest residues represent large, unexploited, biomass resources, but that dedicated energy crops and short rotation coppices on agricultural land have the largest biomass potential in the medium-long term. However, this potential is contingent upon assumptions regarding surplus agricultural land available to grow energy crops and the yields themselves. These studies therefore highlight the importance of accounting for land-use competition between food and bioenergy production as well as for farming practices and the pedoclimatic context influencing yields. They also indicate the need to complement these large scale assessments with more regional and local-scale studies.

The agropedoclimatic context will be key in determining if and where a given crop species can be grown, together with the appropriate cropping technique and the corresponding yield, production cost, and environmental impacts. As many crop species can be grown at a given place (resulting in land-use competition), it is their relative profitability (income minus production cost) that determines land-use allocation. Very often researchers make strong assumptions on land availability, such as excluding from energy feedstock cultivation the areas necessary to fulfil future requirements in terms of food, feed, and nature preservation ("food, feed, and nature first" paradigm). This is for instance the case in Fischer et al. (2010) and de Wit and Faaij (2010) (REFUEL project) studies, in which biomass supply curves were generated for EU27 based on detailed agropedoclimatic potential, accounting only for production costs. van der Hilst et al. (2010), Ugarte and Ray (2000), and Ballarin et al. (2011) compared net present values of lignocellulosic crops and food crop rotations to allocate land on a limited share of the agricultural area, given exogeneous biomass prices. However, there is no existing market for lignocellulosic crops, which are new commodities. Their price will be determined locally, as transportation costs are expected to be high with respect to the biomass value (due to its low density). Farmers are likely to grow them only if a local bioenergy chain emerges and if the price they are offered covers at least their opportunity cost. The latter depends on the foregone revenues from the best alternative, the production cost, and the delivery cost (to a conversion plant). If foregone revenues due to land-use substitution and competition are not accounted for, then part of the biomass opportunity cost goes unaccounted for, leading to its underestimation. The above-mentioned studies therefore most likely misestimate biomass supply costs. If, instead, land use competition is more accurately taken into account, we should be able to better estimate the type and quantity of biomass that can be supplied as well as the associated opportunity cost, providing thereby a more detailed picture of what can happen at the local level.

The relative location of feedstock and bioenergy facilities has an impact on the supply cost of the facility, but also on the choice of the type of biomass delivered to the plant, for low transport costs can compensate for a difference in farm gate/on-site cost between two types of biomass. Many studies addressed the issue of the optimum siting and/or sizing of conversion plants, in relationship to their competitiveness. But they often account for (fixed) exogeneous biomass quantities and costs (Leduc et al., 2009; Tittmann et al., 2010; Lensink and Londo, 2010; Londo et al., 2010). Schmidt et al. (2010) optimized the whole supply chain but only considered forest biomass.

Finally, it is important to have a detailed modelling of the supply side to better account for the actual lignocellulosic biomass supply and its impact on land-use change. Production, land-use, and resource allocation decisions are taken locally by private landowners or managers (i.e., farmers or forest managers), that basically maximize their gross margin, subjected to technical and policy constraints and accounting for the price context. Microeconomic, farm-based, agricultural supply models are widely used to assess the impacts of agri-environmental and energy policies, in the field of agricultural economics. They have been used to assess the competitiveness and impacts of the first generation biofuels (Rozakis and Sourie, 2005; Sourie et al., 2005; Guindé et al., 2008). For instance, Rozakis and Sourie (2005) showed that tax exemptions for first generation biofuels in France were overestimated and could be decreased by 10-20% with no risk for the viability of these chains. However, these models are generally not spatially explicit and do not account for the location of conversion plants, nor for transportation issues. If they do try to locate biomass production, it is generally by means of downscaling or probability maps.

To accurately address the issue of the sustainability of agricultural and forest lignocellulosic bioenergy chains (in terms of competitiveness and environmental impacts), it is important to account, at a local level, for land-use competition and substitution, spatial distribution of bioenergy crops and biomass production, and logistics constraints (Hellmann and Verburg, 2011; Petersen, 2008). The location of conversion plants with regard to feedstock availability is a specific issue: it plays a role in both competitiveness - through transportation costs - and environmental impacts -through fuel consumption for instance.

To our knowledge, no study has accounted for all these factors. In this paper, we set out to do so. We model biomass supply at a local scale accounting for agricultural and forest biomass in a detailed manner, land-use competition, transportation costs, and the optimal location of bioenergy facilities. At the same time we account for the competition between agricultural and forest biomass for energy uses. Within an overall project to assess the competitiveness and environmental impacts of the production of bioenergy from lignocellulosic biomass, we examine plant location, land allocation, biomass supply costs, and environmental impacts in relation to the demand for cellulosic feedstock at the regional (Nuts 2) level. More precisely, we address the following questions: i) what type and quantity of biomass can be supplied at the regional level and for what price depending on the economic context; ii) where will the biomass source be cultivated and where will the conversion plants be located in relationship to supply location; and iii) what is the impact of plant location on both the choice of biomass to be grown and the supply cost?

To tackle these questions, we have developed a spatially-explicit regional supply model with a county sub-level for agricultural and forest lignocellulosic biomass. The model maximizes the agricultural and forest gross margins of the region, taking into account all of the following: transportation distances and costs from counties to bioenergy facilities, the (facilities) demand for biomass in primary energy equivalent, soil characteristics, biomass and crop yields and production costs as well as available wood quantities per category, the related stumpage and harvesting costs, and the various potential uses of biomass (food, energy, industry or timber). The model endogenously determines the optimal location of facilities within a region in addition to agricultural land allocation in counties as well as types and quantities of wood supplied.

As an illustration, we have applied this modelling approach to the case of the French Champagne-Ardenne region. It has enabled us to generate the first lignocellulosic biomass supply curves for France, to perform a sensitivity analysis to the food crops price context, and to bring under scrutiny well-accepted claims concerning the production and supply of lignocellulosic biomass in France. It is widely thought that: Miscanthus is the dedicated energy crop to be grown in France; that forest remnants will be massively used for energy purpose; and that perennial dedicated crops will be grown on marginal land thus lower the competition with food crops for land. How do these claims hold up when confronted with our results for the given region?

The article is structured as follows. The methodological aspects involving the modelling approach are covered in Section 1.2. In Section 1.3, the case study and the applied model are described, and the simulation scenarios and hypotheses are introduced. In Section 1.4 we discuss the results. In Section 1.5, we sum up the overall advantages of our spatially-explicit approach and bring under discussion the three above-mentioned claims about the production and supply of lignocellulosic biomass in France. In Section 1.6, perspectives, we make suggestions for further development and applications of the model.

1.2 Methodology

A spatially-explicit regional supply model for agricultural and forest lignocellulosic biomass has been developed, that accounts for two spatial levels : the county and the region. The model maximizes the agricultural and forest incomes of the region, taking into account the demand for lignocellulosic biomass, transportation distances and costs from counties to bioernergy facilities, food and energy crops yields and production costs in relation to soil characteristics, available wood quantities per category and the related stumpage and harvesting costs, and the various potential uses of biomass (food, energy, industry or timber). The model endogenously determines agricultural land allocation, harvested wood quantities per category, as well as the type, quantity, conditioning, and origin of lignocellulosic biomass supplied to bioenergy facilities. It also determines the optimal location of facilities within a region, if it is not initially given. The presented model accounts for two spatial levels: the county and the region. The county has been chosen as the elementary unit as it is an administrative (sub) level for which data are available, and it provides the framework for locating biomass departure and delivery points at the county seats. It is characterised by its agropedoclimatic context, its altitude, and the slope of forest stands. In this model it is the level at which production decisions occur, taking into account technical and economic constraints. I.e, the county iehaves as a farm or forest manager. The region is the relevant level when it comes to drawing the boundaries of the biomass supply area and studying the competition for resources arising when different bioenergy facilities are being set up at the same time or over time. It is the level at which transportation costs and logistics issues are accounted for.

We assume here that agricultural and forest areas are independent, i.e., deforestation and afforestation are not allowed, and that short rotation coppices (SRC) can only be grown on agricultural areas. A schematic overview of the model inputs and outputs is provided in Fig. 1.1. This model is a mixed integer programming model written in GAMS and solved with the CPLEX solver.

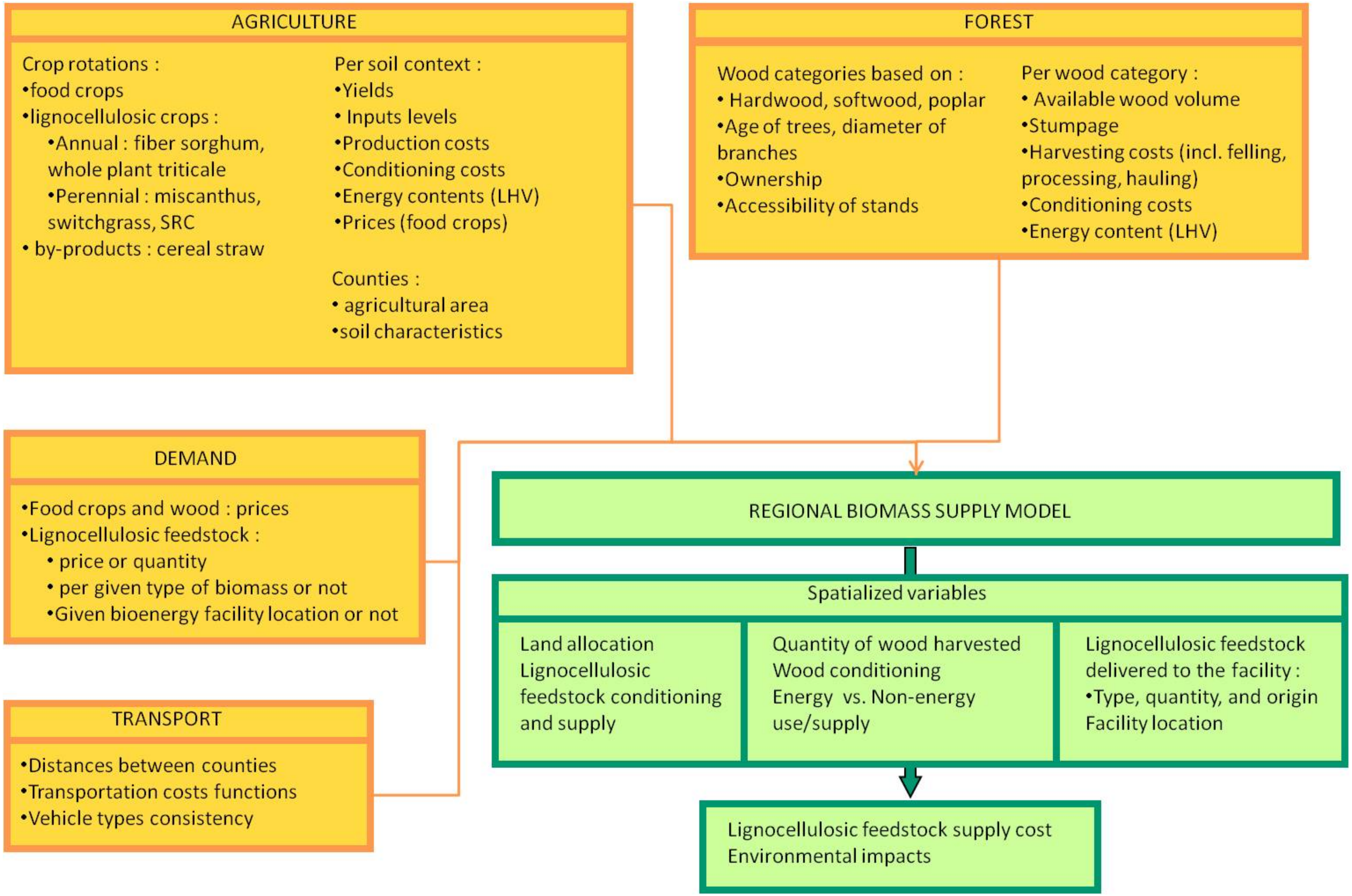


Fig. 1.1. Schematic overview of the model inputs and ouputs

1.2.1 Model description

We provide here a stylised version of the model and then further detail the activities and constraints in the following subsections.

Objective function

The model maximizes the region's gross margin, i.e., the sum of counties' gross margin for agricultural ($\Pi_i^{CROPS}\left(S_i^{ROT}\right)$) and forest ($\Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right)$)activities, including biomass production for bioenergy ($\Pi_i^{ENERGY}\left(X_i^{ENERGY}\right)$), minus transportation costs for the biomass delivered from production sites to bioenergy facilities ($T_{i,j}^{ENERGY}\left(LBD_{i,j}^{ENERGY}\right)$) (Equation (1.1)).

$$\max_{X_i, LBD_{i,j}, (locus_j)} \sum_i \left(\Pi_i^{CROPS}\left(S_i^{ROT}\right) + \Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right) + \right. \\ \left. + \Pi_i^{ENERGY}\left(X_i^{ENERGY}\right)\right) - \sum_{i,j} T_{i,j}^{ENERGY}\left(LBD_{i,j}^{ENERGY}\right) \cdot locus_j \quad (1.1)$$

where i and j are respectively the indices for departure and arrival counties; $LBD_{i,j}^{ENERGY}$ is the amount of lignocellulosic biomass (energy crop, straw or wood) delivered to county j from county i (tons); $locus_j$ is equal to 1 if a bioenergy facility is located in county j and to 0 otherwise.

Constraints

Constraint 1.2 sets that the areas $S_{r,s,i}^{ROT}$ grown with rotations including food and/or energy crops must be less than the total agricultural area UAA_i in each county.

$$\sum_{r,s} S_{r,s,i}^{ROT} \leq UAA_i, \quad \forall i \quad (1.2)$$

Constraint 1.3 links crops production $X_{c,s,i}^{CROPS}$ to the area dedicated to the various crop rotations $S_{r,s,i}^{ROT}$, given the yield $y_{c,s}$ of crop c on soil s and its share $\gamma_{c,r}$ in rotation r.

$$X_{c,s,i}^{CROPS} = \sum_r \left(y_{c,s} \cdot \gamma_{c,r} \cdot S_{r,s,i}^{ROT}\right), \quad \forall c, s, i \quad (1.3)$$

Constraint 1.4 relates the amount of straw that can be used for energy purpose X_i^{EStraw} to the area grown with cereal crops, given $y_{c,i}^{straw}$ the yield of straw from cereal crops c in the county, and limits it to the share α_i that can be exported without harming the soil organic matter content.

$$X_i^{EStraw} \leq \sum_{r,s} \left(\alpha_i \cdot y_{c,i}^{straw} \cdot \gamma_{c,r} \cdot S_{r,s,i}^{ROT} \right), \quad \forall i \tag{1.4}$$

Constraints 1.5 and 1.6 limits the amount of wood that is harvested for energy (X_i^{EWood}) and non-energy (X_i^{NEWood}) uses to the amount available annually($\overline{W_i^{WOOD}}$), accounting for wood density (ρ).

$$W_i^{WOOD} \leq \overline{W_i^{WOOD}}, \quad \forall i \tag{1.5}$$

$$\rho \cdot \left(X_i^{NEWood} + X_i^{EWood} \right) \leq W_i^{WOOD}, \quad \forall i \tag{1.6}$$

The lignocellulosic feedstock supply in each county X_i^{ENERGY} equals the sum of its annual and perennial dedicated crops X_i^{ECrop}, cereal straw X_i^{EStraw}, and wood X_i^{EWood} supply (Equation (1.7)).

$$X_i^{ECrop} + X_i^{EWood} + X_i^{EStraw} = X_i^{ENERGY}, \quad \forall i \tag{1.7}$$

A county i cannot export more lignocellulosic feedstock to other counties j than its own production (1.8).

$$X_i^{ENERGY} \geq \sum_j LBD_{i,j}^{ENERGY}, \quad \forall i \tag{1.8}$$

The total amount of lignocellulosic biomass delivered to a county j must satisfy the facility's demand (D^{ENERGY}), if it exists (i.e. $locus_j = 1$), accounting for the feedstock energy content (lhv^{ENERGY}) (Equation (1.9)).

$$\sum_i LBD_{i,j}^{ENERGY} \cdot lhv^{ENERGY} = D^{ENERGY} \cdot locus_j, \quad \forall j \tag{1.9}$$

$locus_j$ is a binary variable equal to 1 if a bioenergy facility is located in county j and to 0 otherwise. All other variables must be equal to or greater than 0.

$$W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}, S_{r,s,i}^{ROT}, LBD_{i,j}^{ENERGY} \geq 0 \tag{1.10}$$

1.2.2 Agricultural biomass

In this model we have chosen to optimize the area of crop rotations, rather than the area of crops. Crop rotations better take into account the preceding and following crop effects on yields, input consumptions (nitrogen balance for instance) and environmental impacts. Moreover, it facilitates the comparison of crop rotations (composed of annual crops) to perennial crops such as miscanthus and short rotation coppice. We assume that farmers will substitute perennial crops for existing crop rotations and annual dedicated crops, such as whole plant triticale, for equivalent crops in crop rotations. Our crop rotations are based on existing ones or ones that could be used on each of the soil types. We also account for by-products such as cereal straw.

Equations 1.11 to 1.13 detail the components of food crops, dedicated energy crops, and straw gross margins, included in the objective function.

$$\Pi_i^{CROPS}\left(S_i^{ROT}\right) = \sum_{c,s}\left(\left(p_c \cdot y_{c,s} - c_{c,s}^{prod}\right) \cdot \sum_r \gamma_{c,r} \cdot S_{r,s,i}^{ROT}\right) \tag{1.11}$$

$$\Pi_i^{ENERGY}\left(X_i^{ECrop}\right) = \sum_c\left(\left(p^{MWh} \cdot lhv_c - c_c^{cond}\right) \cdot X_{c,i}^{ECrop}\right) \tag{1.12}$$

$$\Pi_i^{ENERGY}\left(X_i^{EStraw}\right) = \left(p^{MWh} \cdot lhv_{straw} - c_{straw}^{cond}\right) \cdot X_i^{EStraw} \tag{1.13}$$

1.2.3 Forest biomass

In this model, forest biomass is accounted for in terms of existing forests according to the following characteristics: area, location, ownership, species, age of trees (young or medium-sized trees and old or big-sized trees), and slope of the plots. Medium-sized trees have small and medium diameter branches, whereas big-sized trees have small, medium and big diameter branches. Knowing the age and composition of forest plots, we can assess the amount of wood of each diameter that is available. Depending on diameter, wood can be conditioned into logs, bundles or wood chips (see Fig.1.2). It is possible to cut trees, to condition and export only a part of the wood, and leave the rest on the ground (e.g. it is often the case of remnants).

Equations 1.14 to 1.15 detail the components of forest activities' gross margins, included in the objective function.

$$\begin{aligned}\Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right) = \sum_{w,cond}\left(p^{wood} \cdot X_{w,cond,i}^{NEWood}\right) - \\ - \sum_{w,cond}\left(c_{w,cond}^{stump} \cdot W_{w,cond,i}^{WOOD} + c_{w,cond}^{harv} \cdot \left(X_{w,cond,i}^{NEWood} + X_{w,cond,i}^{EWood}\right)\right)\end{aligned} \tag{1.14}$$

$$\Pi_i^{ENERGY}\left(X_i^{EWood}\right) = \sum_w p^{MWh} \cdot lhv_w \cdot X_{w,i}^{EWood} \tag{1.15}$$

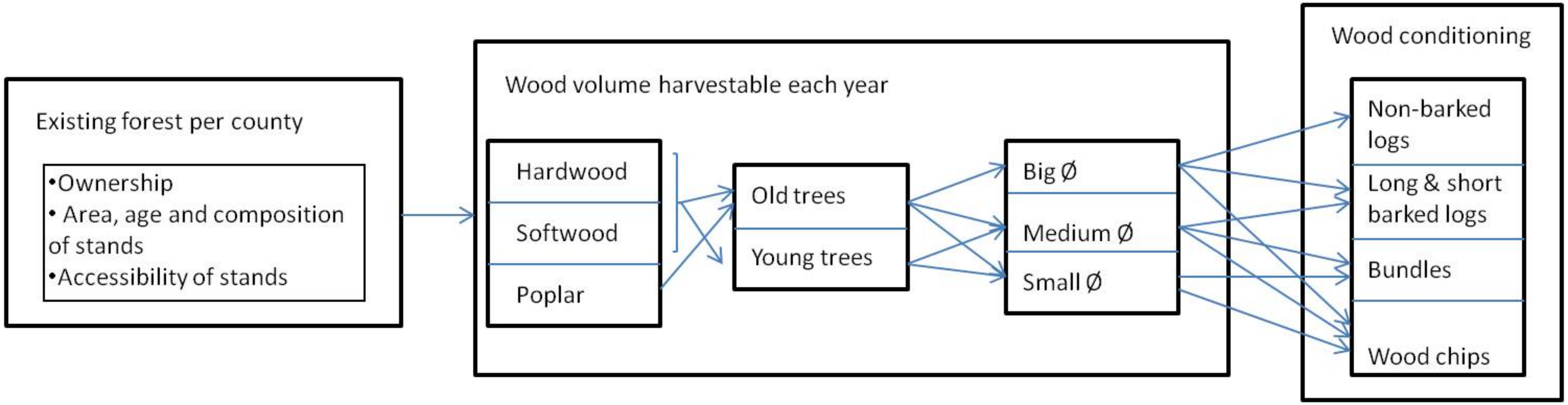


Fig. 1.2. Determination of the annually harvestable wood volume and its potential conditioning, depending on the existing forest characteristics

1.2.4 Demand

We assume here that farmers and forest managers are price-takers. The demand for food crops and non-energy wood is accounted for by means of the regional market prices. The demand for agricultural and/or forest lignocellulosic feedstock is expressed either in terms of i) quantity : i.e., in our case for a matter of simplicity, in primary energy content equivalent; or ii) price: i.e., in euro per unit of primary energy content. The demand can also be spatially located within the region, for instance when a bioenergy facility is to be supplied with lignocellulosic feedstock. For reasons of simplicity and computation time issues, we assume that a facility can only be located at the county seat. The location of the facility can be either fixed (i.e. *locus* becomes a parameter) or optimized by the model (i.e. *locus* is a decision variable).

1.2.5 Transportation

In this model, we consider simplified transportation costs per ton and per kilometre while minimizing total lignocellulosic feedstock supply cost, including delivery costs[2]. The cost ($t_{c,cond,vcl,i,j}$ or $t^{EWood}_{w,cond,vcl,i,j}$) of transporting a ton of lignocellulosic feedstock from county i to county j depends on : i) the distance $d_{i,j}$ between the two counties; ii) the type of conditionning (*cond*) of the biomass (e.g., silage, high density bales, logs, wood chips, etc.), which influences its density; iii) the type of vehicle (*vcl*) which is being used. We assume that all biomass is already available at the county seat. However, when the source of biomass and the facility are located within the same county, the transportation charge is a fixed one.

Agricultural biomass transportation costs per ton are accounted for in the form of a piecewise linear function of the distance, over distance class intervals (Equation (1.17)). We consider a fixed cost $\epsilon_{c,cond,vcl,cld}$ for intra-county delivery only (i.e., $i = j$ and $d_{i,j} = 0$), which is otherwise nil.

$$T^{ECrops}_{i,j}\left(LBD^{ECrops}_{c,i,j}\right) = \sum_{c,cond,vcl}\left(t_{c,cond,vcl,i,j} \cdot LBD^{ECrops}_{c,cond,vcl,i,j}\right) \tag{1.16}$$

with :

$$t^{ECrop}_{c,cond,vcl,i,j} = \delta_{c,cond,vcl,cld} \cdot d_{i,j} + \epsilon_{c,cond,vcl,cld} \tag{1.17}$$

[2]This is equivalent to maximizing the sum of counties' gross margin for agricultural activities, including biomass production for bioenergy, minus biomass delivery cost from production sites to a bioenergy facility

and cld being the distance class to which belong $d_{i,j}$; $\delta_{c,cond,vcl,cld}$ and $\epsilon_{c,cond,vcl,cld}$ being the parameters of the dedicated crop transportation cost function (in €/km and €, respectively).

Forest biomass transportation costs per ton are accounted for in the form of a quadratic function of the distance (Equation (1.19)).

$$T_{i,j}^{EWood}\left(LBD_{w,i,j}^{EWood}\right) = \sum_{w,cond,vcl}\left(t_{w,cond,vcl,i,j}^{EWood} \cdot LBD_{c,cond,vcl,i,j}^{EWood}\right) \tag{1.18}$$

with :

$$t_{w,cond,vcl,i,j}^{EWood} = \vartheta_{c,cond,vcl}^{EWood} \cdot d_{i,j}^2 + \delta_{c,cond,vcl}^{EWood} \cdot d_{i,j} + \epsilon_{w,cond,vcl}^{EWood} \tag{1.19}$$

and $\vartheta_{c,cond,vcl}^{EWood}$, $\delta_{c,cond,vcl}^{EWood}$, and $\epsilon_{w,cond,vcl}^{EWood}$ being the parameters of the quadratic transportation cost function for wood (in €$/km^2$, €/km, and € respectively).

1.3 Case study

The above-described spatially-explicit model and the associated generic methodology were initially developed within an interdisciplinary project, in collaboration with agricultural and forest technical institutes. To test the methodology, the French Champagne-Ardenne region was selected for numerous reasons. It is made up of 146 counties with both agricultural and forest activities and different types of lignocellulosic crops can be grown there [3]. Moreover, research and development activities focused on second generation biofuels are already being carried out in this region. We decided to only account for the utilised agricultural area (UAA) of cash crop farms (Types of Farming 13 and 14 in accordance with the FADN classification), as we do not model breeding and dairy farms. We do not account for permanent grassland areas in the model, as they are fixed over time, and therefore removed them from the cash crop farms UAA in each county in equation 1.2). Below, we first describe the tested scenarii and the hypotheses. Data sources for the test region are then detailed, and the validation of the model is presented.

1.3.1 Scenarii and hypotheses

First, we simulate individual biomass supply curves for switchgrass, miscanthus, whole plant triticale, fiber sorghum, poplar SRC, forest biomass, and wood chips (either from

[3]Detailed information on the agricultural and forest sector of the region can be found in a project deliverable (Bamière, L. et al., 2007)

poplar SRC or forest biomass). To do so, we introduce a price for the bioenergy feedstock under consideration in the objective function and we then simulate the quantity of this feedstock that is made available at the regional level.

Second, we simulate the potential total lignocellulosic biomass supply curve for the Champagne-Ardenne region, accounting for the competition between the various biomass feedstock sources. To do so, we introduce a price for lignocellulosic feedstock (in MWh equivalent) in the objective function and we then simulate the type and quantity of the various feedstock sources that are made available at the region level.

In both cases, locus is a parameter set to 0 and equations 1.8 and 1.9 are removed.

Finally we simulate the setting up of a second generation ethanol production facility. The facility is characterized by its use of enzymatic hydrolysis and fermentation to produce bioethanol from lignocellulosic biomass, with a target production of 180 million liters of ethanol per year. These characteristics correspond to a project under study in the region[4]. To do so, we introduce a demand for lignocellulosic biomass in equation 1.9, that forces the model to satisfy the facility's demand. We look for the best facility location, the type and quantity of biomass supplied as well as the corresponding supply costs. As we optimize the facility location, locus is considered as a variable.

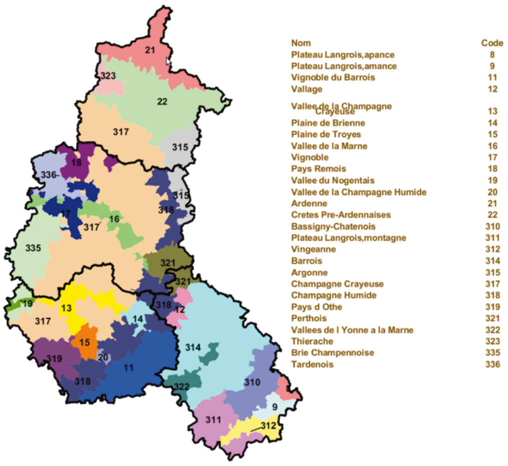
In each case, we perform a sensitivity analysis of our results to the agricultural prices context.

1.3.2 Soil and agricultural data

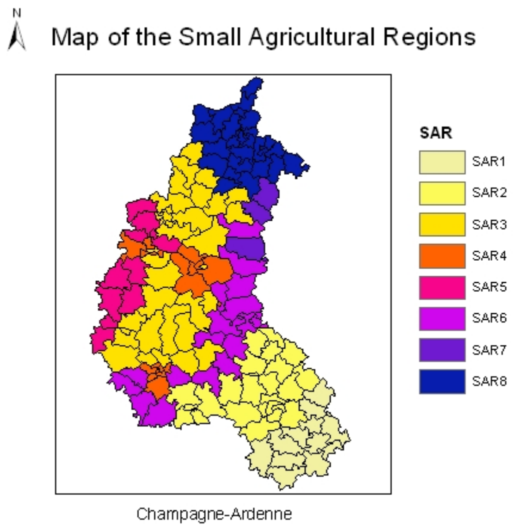
We have chosen to account for the agropedoclimatic context by the use of Small Agricultural Regions (SARs, INSEE classification). Small Agricultural Regions define homogeneous agricultural areas from the pedoclimatic and production context point of view. For a matter of simplicity, the 27 SARs of the Champagne-Ardennes region (Fig. 1.3a) were clustered into 8 homogeneous groups, hereafter mentioned as SAR1 to 8 (Fig. 1.3b). The maps of these 8 SARs and the counties were then overlaid to determine the dominant SAR in each county.

We first identified the food and energy crops that are or could be grown on each SAR, as well as the existing crop rotation patterns in the region. We then conceived the crop rotations to be included in the model, based on this information. In Champagne-Ardenne, cropping systems are very diversified with a large range of heads of crop rotations including rapeseed, beetroots, peas, and vegetables. A wide range of possible crop rotations therefore exists. However, in our case, the actual crop rotations adhere to three main

[4]Futurol-Procethol2G project : http://www.projet-futurol.com/index-uk.php



(a) Map of the 27 Small Agricultural Regions of the Champagne-Ardenne region.



(b) Map of the 8 groups of Small Agricultural Regions (SAR1 to SAR8) of the Champagne-Ardenne region.

Fig. 1.3

patterns. The eligible food crops were inserted into these patterns to obtain 23 food crop rotations (see tables 1.17 to 1.19 in appendix). Concerning annual dedicated crops, whole-plant triticale substitutes for barley in rotations, while fibre sorghum substitutes for maize. Miscanthus and switchgrass require 16-year rotations, including one year to ready the plot. They are harvested every year as of the third year until the fifteenth year. Given this procedure, we obtained 9 energy crop rotations (see Table 1.20 in appendix). As mentioned before, short rotation coppices are only grown on agricultural areas. Three types of poplar SRC were differentiated based on the suitable pedoclimatic context for their production, the cropping technique, and the associated yield level. Poplar SRC require 21-year rotations harvested every 7 years.

Finally, any available data on agricultural practices, crop yields and production costs were gathered for each SAR. Yield data culled from different regional sources were compared so as to compute average yields for conventional crops over a 10-year period for each SAR. Three types of wheat are differentiated based on the preceding crop, leading to different yield and production cost levels. Data from the same regional sources involving yields were used to compute average production costs (including seeds, fertilisers, herbicides, and pesticides) over the 10-year period for each food crop in each SAR. Yields and production costs for dedicated energy crops were estimated from field trial results. For poplar SRC and each perennial crop, an average annual yield and an equivalent annual cost are computed over the whole duration of the rotation (including the non-productive years, and with a 5% discount rate for the costs). Yield and production cost data for crops and SRC are gathered in Table 1.1, Table 1.2 and Table 1.3 respectively. For a matter of comparison and consistency, we use the equivalent annual costs of crop rotations and SRC in the model.

We perform the simulations for three agricultural price context scenarios (see Table 1.4). In the benchmark scenario, food crop prices correspond to the mean prices for 1993-2007. In the "low prices" and a "high prices" scenarios, they correspond respectively to the 1^{st} and the 9^{th}decile of 1993–2007 prices.

To assess the environmental impact of a demand for agricultural lignocellulosic biomass, in terms of pesticide and herbicide use, we use data on the average number of treatments for each crop per hectare, per year, and per SAR (c.f. Table 1.5). We compute : i)the average number of treatments per hectare for each county, each SAR, and for the region; ii) the total number of treatments for each county, each SAR, and for the region.

Moreover, most of the region is classified as "‘vulnerable zone"’ under the Nitrates Directive (Directive 91/676/EEC, see figure 1.18). As a consequence, agricultural areas are subjected to constraints on nitrogen fertilisation practices. Therefore, we also assess nitrogen fertilision level, using data on average fertilisation level for each crop per hectare, per year, and per SAR (c.f. Table 1.6). This information on nitrogen input levels cannot be used as a proxy to assess environmental impacts due to fertilisation. To do so, one should assess excess nitrogen considering crops needs and input use, which we do not.

Detailed information on soil and agricultural data sources and processing can be found in appendix (c.f. table 1.16).

	SAR1		SAR2		SAR3		SAR4	
	yield	production cost	yield	production cost	yield	production cost	yield	production cost
Wheat (after Wheat)	6.0	340.0	6.5	340.0	7.9	365.4	8.4	370.0
Wheat (standard)	6.4	330.0	7.0	330.0	8.5	355.4	9.0	360.0
Wheat (after good preceding crop)	6.7	315.0	7.4	315.0	8.9	340.4	9.5	345.0
Spring Barley	4.6	350.0	5.1	250.0	6.7	275.0	7.0	300.0
Winter Barley	6.2	0.0	6.7	345.0	8.0	340.0	8.5	350.0
Rapeseed	3.1	345.0	3.1	390.0	3.6	365.0	4.0	370.0
Sunflower	2.5	360.0	2.5	280.0	3.0	310.0	3.3	280.0
Maize	6.5	280.0	6.5	380.0	9.0	400.0	10.0	460.0
Spring Pea	3.9	380.0	4.0	270.0	4.3	280.0	5.5	270.0
Winter Pea	4.3	250.0	4.3	235.0	4.3	260.0	4.5	260.0
Horsebean Pea	4.3	0.0	4.3	285.0	4.3	285.0	4.5	285.0
Sugar Beet	0.0	0.0	0.0	0.0	90.0	700.0	90.0	700.0
Food Potatoe	0.0	0.0	0.0	0.0	48.5	2290.0	48.5	2290.0
Starch Potatoe	0.0	0.0	0.0	0.0	45.0	1250.0	45.0	1250.0
Alfalfa (1st year)	0.0	0.0	0.0	0.0	14.0	400.0	0.0	0.0
Alfalfa (2nd year)	0.0	0.0	0.0	0.0	14.0	220.0	0.0	0.0
Alfalfa (3rd year)	0.0	0.0	0.0	0.0	12.0	200.0	0.0	0.0
Miscanthus	8.1	496.1	8.1	496.1	8.1	496.1	16.3	496.1
Whole Plant Triticale	10.0	250.0	12.5	250.0	15.0	250.0	16.0	250.0
Switchgrass	10.5	148.9	10.5	148.9	8.8	148.9	17.5	148.9
Fiber Sorghum	0.0	0.0	8.0	250.0	6.0	250.0	14.0	250.0

Table 1.1
Yields (in dry matter tons/ha) and production costs (in €/ha) for food and energy crops, depending on the small agricultural region (SAR), part 1.

	SAR5		SAR6		SAR7	
	yield	production cost	yield	production cost	yield	production cost
Wheat (after Wheat)	7.4	380.0	6.9	375.0	6.7	290.0
Wheat (standard)	8.0	370.0	7.4	365.0	7.2	280.0
Wheat (after good preceding crop)	8.4	355.0	7.8	350.0	7.6	265.0
Spring Barley	6.1	305.0	5.5	250.0	6.0	230.0
Winter Barley	7.8	345.0	6.9	345.0	7.0	260.0
Rapeseed	3.5	368.0	3.3	370.0	3.0	270.0
Sunflower	3.0	280.0	3.0	280.0	2.5	280.0
Maize	9.5	430.0	8.0	400.0	9.0	400.0
Spring Pea	5.0	280.0	4.3	270.0	4.2	230.0
Winter Pea	4.3	258.0	4.3	245.0	4.0	230.0
Horsebean Pea	4.3	285.0	4.3	285.0	3.5	285.0
Sugar Beet	80.0	700.0	0.0	0.0	80.0	0.0
Food Potatoe	48.5	2290.0	0.0	0.0	0.0	0.0
Starch Potatoe	45.0	1250.0	0.0	0.0	0.0	0.0
Alfalfa (1st year)	13.0	400.0	0.0	0.0	0.0	0.0
Alfalfa (2nd year)	13.0	220.0	0.0	0.0	0.0	0.0
Alfalfa (3rd year)	9.0	200.0	0.0	0.0	0.0	0.0
Miscanthus	14.6	496.1	12.2	496.1	9.8	496.1
Whole Plant Triticale	15.0	250.0	14.0	250.0	14.0	250.0
Switchgrass	15.8	148.9	13.1	148.9	10.5	148.9
Fiber Sorghum	12.0	250.0	8.0	250.0	8.0	250.0

Table 1.2
Yields (in dry matter tons/ha) and production costs (in €/ha) for food and energy crops, depending on the small agricultural region (SAR), part 2.

	yield	production cost
SRC8	8	485.2
SRC10	10	571.2
SRC12	12	657.1

Table 1.3
Short Rotation Coppices' yields (in dry matter tons/ha/year) and production costs (in €/ha/ha).

	Low	Benchmark case	High
Wheat (after Wheat)	83.65	111.13	148.45
Wheat (standard)	83.65	111.13	148.45
Wheat (after good preceding crop)	83.65	111.13	148.45
Spring Barley	92.42	122.79	164.02
Winter Barley	77.93	103.53	138.31
Rapeseed	136.02	204.38	308.56
Sunflower	142.46	214.06	323.17
Maize	70.39	99.72	142.15
Spring Pea	94.91	126.08	168.43
Winter Pea	94.91	126.08	168.43
Horsebean Pea	97.25	129.20	172.60
Sugar Beet	32.99	32.99	32.99
Food Potatoe	136.74	136.74	136.74
Starch Potatoe	42.68	42.68	42.68
Alfalfa (1st year)	65.39	65.39	65.39
Alfalfa (2nd year)	65.39	65.39	65.39
Alfalfa (3rd year)	65.39	65.39	65.39

Table 1.4
Food crop prices for the "low", "benchmark", and "high" agricultural price scenarios (in €/ton).

	SAR1-2	SAR3-7		SAR1-2	SAR3-7
Wheat	6	9	Food Potatoe		19
Spring Barley	5	5	Starch Potatoe		19
Winter Barley	6	5	Alfalfa 1		2
Maize	3	3	Alfalfa 2		1
Rapeseed	8	6	Alfalfa 3		1
Sunflower	2	2	Miscanthus	0.3125	0.3125
Spring Pea	4.5	5	Switchgrass	0.375	0.3125
Winter Pea	4	5	Whole Plant Triticale	3	2
Horsebean Pea	7	6	Fiber Sorghum	2	2
Sugar Beet		6	Poplar SRC	0.0762	0.0762

Table 1.5
Average number of pesticide and herbicide treatments per crop, depending on the small agricultural region (SAR) (in number of treatments/ha/year)

	SAR1	SAR2	SAR3	SAR4	SAR5	SAR6	SAR7
Wheat	160	180	220	180	200	200	180
Spring Barley	100	125	135	120	125	120	130
Winter Barley	130	155	170	170	160	150.25	160
Maize	175	180	195	195	195	175	170
Rapeseed	50	50	50	50	50	50	50
Sunflower	140	140	145	160	150	140	150
Sugar Beet			130	130	100		
Food Potatoe			170	170	170		
Starch Potatoe			160	160	160		
Miscanthus	60	60	60	80	80	80	80
Switchgrass	100	100	120	120	120	120	120
Whole Plant Triticale	120	120	150	150	150	140	140
Fiber Sorghum		80	60	140	120	80	80

Table 1.6
Average nitrogen fertilisation level per crop, depending on the small agricultural region (SAR) (in uN/ha/year)

1.3.3 Forest data

First, the characteristics of the existing forest were determined. Secondly, the quantity of wood available per diameter category was assessed using the previous information. Thirdly, data dealing with harvest costs, conditioning costs, and prices were gathered for each category.

Harvest costs depend on the species, the diameter, the slope of the plots, and the distance to the nearest access road.

The French National Forest Survey (IFN) is the main data source for the forest feature in our model. In the IFN, each type of forest stand (e.g., high forest, coppice, etc.) is characterised by its age, the share of the different species (e.g., hardwood, softwood, and poplars), its wood volume, and its annual growth. Based on this information, a harvesting scenario is applied (e.g., thinning, improvement and regeneration cutting) that determines the gross annual harvestable wood volume and the types of harvestable products. Harvesting losses and wood volumes that are unharvestable due to technical logging difficulties or the reluctance of small private owners, are then deducted from the gross annual wood volume to obtain the net annual harvestable wood volume for each county. Harvesting costs (including felling cost, tree processing, and hauling costs), stumpage (the price to be paid to a land owner by an operator to harvest standing timber on his land) as well as wood prices were provided for Champagne-Ardenne by the French Association of Forest Cooperatives (Union des Coopératives Forestières de France, UCFF) and were harmonised with those from the French National Forestry Service (Office National des Forêts, ONF). Wood prices are provided in table 1.7. Examples of harvesting costs and stumpage are provided in appendix in tables 1.21 and 1.22.

Detailed information on forest data sources and processing can be found in appendix (c.f. table 1.16).

	Non-barked logs	Long-barked logs	Short-barked logs	Bundles	Wood chips
Softwood	120	48	63.6	55	53.0
Poplar	75	45		55	34.8
Hardwood	102.4	53		55	43.9

Table 1.7
Wood prices for non-energy use depending on the species and the conditioning (in €/ fresh ton).

	Switchgrass	Miscanthus	W.P. Triticale	Fiber Sorghum	Straw	Poplar SRC
LHV (MWh/ dry ton)	4.643	4.170	4.170	4.170	4.170	5.004
	Hardwood	Softwood	Poplar			
LHV (MWh/ std. ton) (moisture degree)	2.3107 (50%)	2.78856 (45%)	1.83177 (55%)			

Table 1.8
Lower heating values of the various lignocellulosic biomass sources, in MWh/tons, depending on their reference moisture degree.

1.3.4 Facility and demand data

In this study, we simulate the setting up of a second generation ethanol production facility. As mentioned above, the facility is characterized by its use of enzymatic hydrolysis and fermentation to produce bioethanol from lignocellulosic biomass, with a target production of 180 million liters of ethanol per year. This corresponds to an energy production equivalent to 1,064 10^6 MWh[5]. Given the current process energy efficiency of 0.39 (Schmidt et al., 2010) and a 7,000 hour/year workload hypothesis, the facility has a size of 389.8 MW (biomass input). This implies a demand for lignocellulosic feedstock equivalent to 2,728,612 MWh.

We use the lower heating values (LHV) of the various lignocellulosic biomass sources to convert tons into MWh (c.f. Table 1.8).

1.3.5 Transportation data

We use distances that minimize transportation time between counties, which is what road haulage contractors tend to do. Our distance matrix takes into account the road network and the topography (people drive faster on flat stretches than on hilly roads) as well as peak and off-peak hours. Transportation costs per ton and kilometre are calculated using the trinomial formula from the "French National Road Center" (Centre National Routier, CNR,2008 data), based on kilometric costs, hourly rates, and fixed costs as well as the type of vehicle which is being used. The choice of the vehicle depends on the type of biomass, its conditioning, the slope of the forest stand, and the distance to cover. For instance, a five-axle trailer truck transports straw bales over a long distance and a tractor transports them over a short distance (less than 25 km). In practice, costs also vary according to distance because the customer is required to pay for the return trip for short distances, whereas for longer distances the road haulage contractor pays for it.

[5]We assume ethanol has an energy content equivalent to 5.91 kWh/L, or 21 283 kJ/L.

	2007 observed data	2007 simulated data
Cereal crops	62.91%	70.97%
Oilseed crops	19.19%	16.27%
Protein crops	1.39%	2.86%
Sugar beet	9.47%	8.46%
Potatoes	1.68%	1.44%
Alfalfa	5.36%	0%

Table 1.9
Observed and simulated land-use share for the main crop categories, expressed in percentage of the represented utilised agricultural area.

Dedicated crop transportation costs per oven dry ton and kilometre, for each type of conditioning and the relevant vehicles, are provided in appendix in table 1.23 in the form of piecewise linear functions. Wood transportation costs per ton and kilometre for each type of conditioning and the relevant vehicles are provided in appendix in table 1.24 in the form of transportation cost functions. Detailed information on transportation data sources and processing can be found in appendix (c.f. table 1.16).

1.3.6 Validation

To validate our model, we compared the simulated regional land use to the observed 2007 situation in Champagne-Ardenne. The validation scenario entails maximizing the sum of counties gross margins, given the 2006 agricultural prices in the region, and subjected to constraints on the sugar beet, starch potatoes, and food potatoes areas at the *département* level. These crops are generally subjected to quotas and/or contracts and they require specific equipment. Their production is therefore quite stable over time. We compared our simulated land use to data for farms growing cereal, oilseed, and protein crops provided by the French agricultural bureau of statistics (Statistique Agricole Annuelle and Enquête structure 2007) at the *département* level, which is the smallest administrative level for which data are available. Table 1.9 shows that they are quite similar, except for alfalfa for which area is underestimated. This is often the case in micro-economic agricultural supply models, for farmers generally grow alfalfa for dehydration cooperatives in which they are shareholders.

1.4 Results

1.4.1 Individual biomass supply curves

Benchmark case

Fig. 1.4 shows that perennial crops have a higher energy supply potential than annual crops and wood in the Champagne-Ardenne region. Among dedicated crops, Switchgrass is the most promising in terms of quantity and cost (it is the second cheapest). Table 1.10 provides a comparison of the opportunity costs of the first MWh equivalent of biomass that is made available for the various lignocellulosic sources. It is noticeable that, apart from Fiber Sorghum, Miscanthus is the least profitable although currently in France it is the most highly cultivated. This finding highlights the importance and influence of the supply chain, and especially of the rhizomes providers.

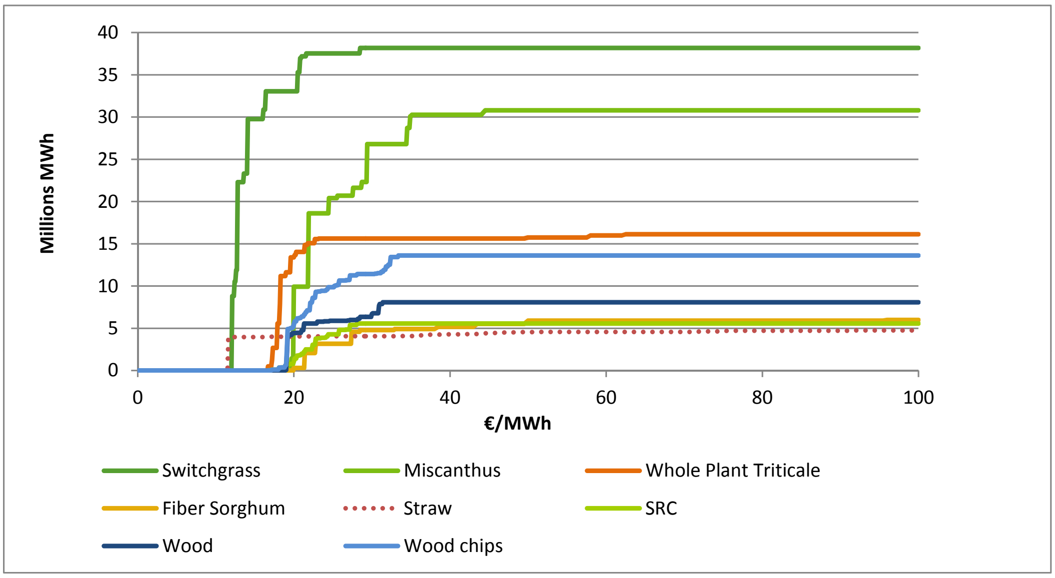


Fig. 1.4. Supply curve for each type of lignocellulosic biomass in the benchmark case.

Straw happens to be the cheapest biomass source, though with a limited potential. However, its opportunity cost, corresponding to its fertilising value in the model, is underestimated as it does not reflect farmers' willingness to supply their straw. The

	Opportunity cost of the first unit of biomass produced in the region (€/MWh)		
	Low	Benchmark	High
Miscanthus	17.1	19.7	24.9
Switchgrass	9.5	12.1	16.5
Whole Plant Triticale	12.4	16.7	22
Straw	11.6	11.6	11.6
Fiber Sorghum	14.7	20	28.3
Poplar SRC	13.7	16.8	21.1
Wood	19	19	19
Wood chips (from SRC and forest biomass)	13.7	16.8	19

Table 1.10
Comparison of the opportunity costs of the first MWh equivalent of each type of biomass produced in the region (in euro/MWh with a precision of 0.1 euro) and for three agricultural price scenarios. These opportunity costs correspond to the intersection of the supply curve with the X-axis.

latter has been investigated in a survey by Arvalis (ARVALIS/ONIDOL, 2009b), but was not accounted for in this study due to non-linearities and computer time issues.

It is generally advocated that there are millions of tons of wood remnants that are currently not harvested in France and are thus expected to help reach the renewable energy targets without hindering other wood uses (ADEME et al., 2009). Fig. 1.5 shows that energy and non-energy uses compete for wood that is already harvested. It can be seen that the total amount of harvested wood, no matter the use, remains nearly constant. It actually increases by 0.12% when wood starts to be used for energy purposes, which is due to an increase by 1.7% in the amount of small diameter branches harvested (i.e., remnants). Fig. 1.6 shows that small diameter branches as well as big diameter branches are used as energy sources. These results are consistent with the current situation. This can be explained by the fact that remnants are not currently harvested because it is not profitable, no matter the potential use, due, for instance, to accessibility issues that increase costs for instance. The types of conditioning chosen on-site are mainly wood chips and logs. This will imply extra costs to "chip" the logs at the biorefinery, if necessary. Table 1.11 provides details on the cost of wood per species and type of conditioning. Wood is diverted from its non-energy uses (timber, pulp and paper, etc.) from 19 €/MWh on, starting with softwood and hardwood small and medium diameter branches, conditioned into wood chips, bundles, and finally logs.

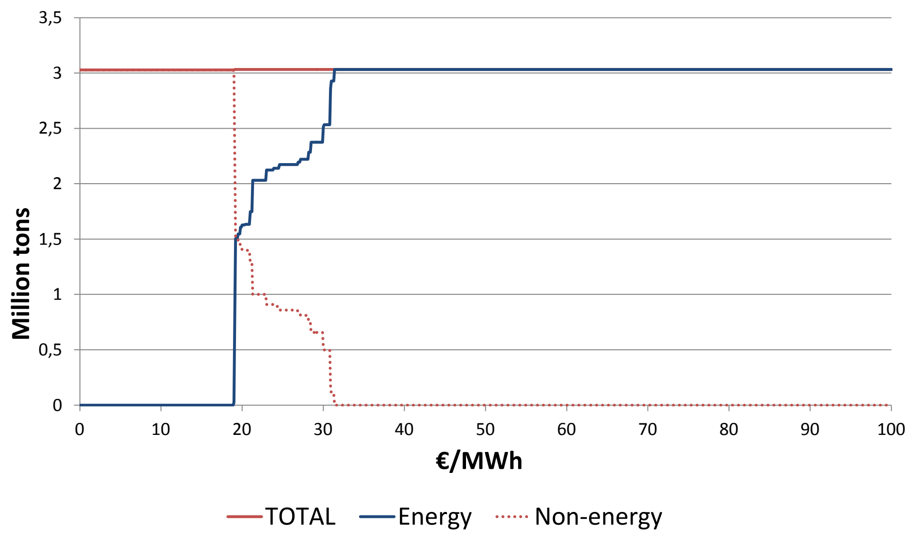


Fig. 1.5. Wood quantities (in fresh tons) dedicated to energy and non-energy uses depending on the price offered (in €/MWh equivalent).

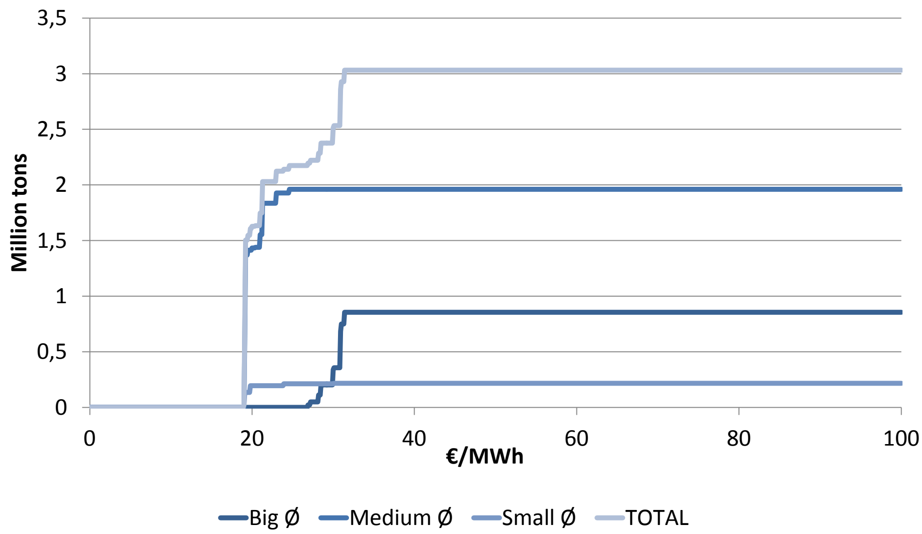


Fig. 1.6. Wood quantities (in fresh tons) sold for energy use per branch diameter (small, medium, big), depending on the price offered (in €/MWh equivalent).

	Opportunity cost of the first MWh harvested		
	Log	Bundle	Wood chips
Softwood	21	19.8	19.1
Hardwood	23	23.9	19
Poplar	24.6	30.1	*

Table 1.11
Opportunity costs of the first MWh of wood harvested for energy uses, detailed per species and type of conditioning (with a precision of 0.1 euro/MWh).

Impact of the agricultural prices economic context

The agricultural price context mainly influences the opportunity cost of lignocellulosic crops, while only marginally modifying their relative profitability. Switchgrass and Miscanthus remain respectively the cheapest and the most expensive dedicated crops. Wood supply is not influenced by the agricultural price context scenarios as we account for neither afforestation nor deforestation. Wood is thus more interesting in the case of high agricultural prices. Individual supply curves for the low and high agricultural price context are provided in figure 1.7 and 1.8.

1.4.2 Biomass supply curve (all biomass sources considered)

Individual supply curves provide insight in the potential supply and the related opportunity cost for each biomass type, and allow for comparisons (cf. Subsection 1.4.1). However, in practice, the various biomass sources will compete for the supply of energy feedstock and the various dedicated crops will also compete for agricultural land. As their yields and production costs vary from one small agricultural region to another, their relative profitability can vary accordingly. Due to the existence of fixed and variable production costs, the relative profitability of perennial dedicated crops also varies with the price paid per unit of energy content (in euro/MWh). For all these reasons, we expect that allowing for competition between the various biomass sources will increase the amount of lignocellusic feedstock supplied for a given price. In addition, it provides usefull information on the composition of the optimal feedstock mix that is made available for a given price.

Benchmark case

The results concerning the type and minimum opportunity cost of the biomass sources which compose the whole supply (see Fig. 1.10 and Table 1.12) are quite consistent with

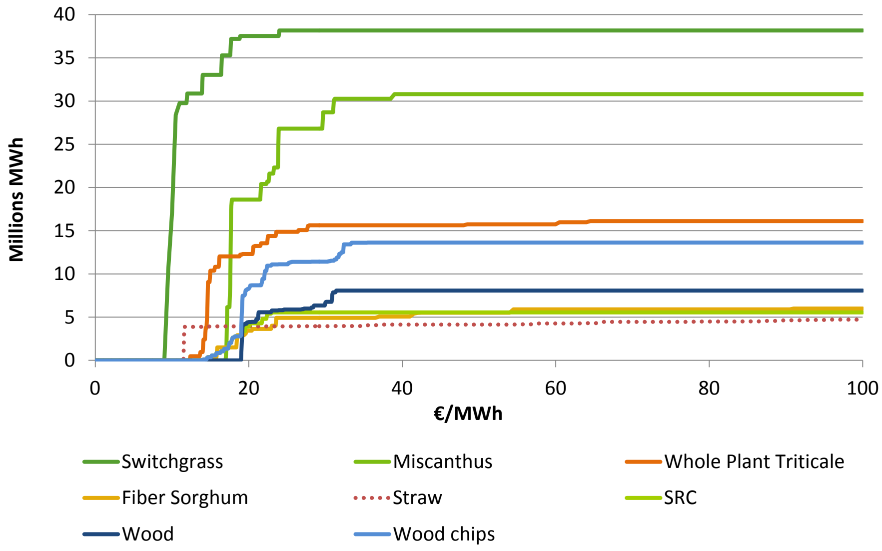


Fig. 1.7. Supply curve for each type of lignocellulosic biomass in the low agricultural price context (1st decile of 1993-2007 prices).

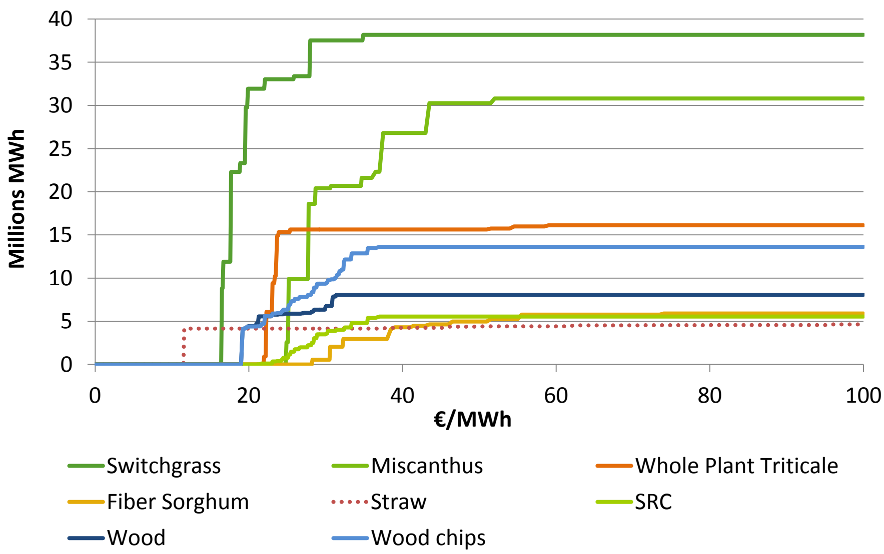


Fig. 1.8. Supply curve for each type of lignocellulosic biomass in the high agricultural price context (9th decile of 1993-2007 prices).

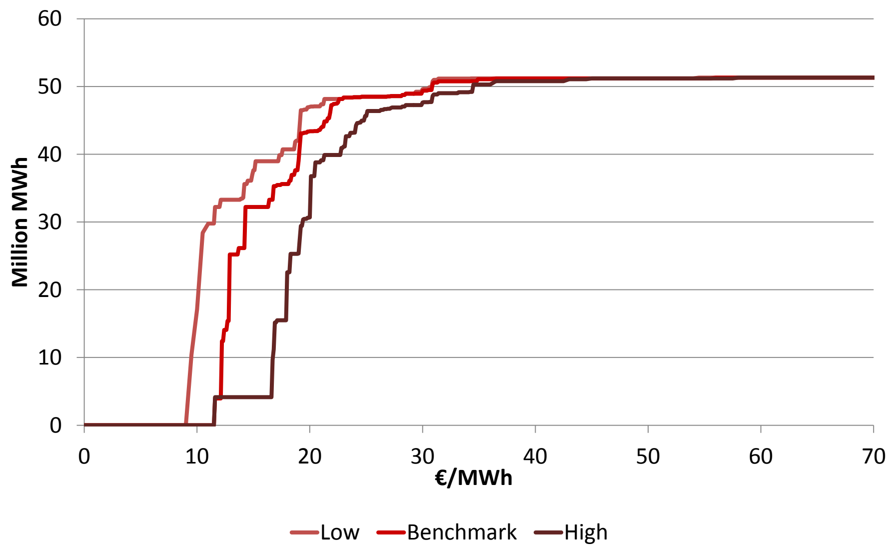


Fig. 1.9. Lignocellulosic biomass supply curves depending on the agricultural price context (low, benchmark, high).

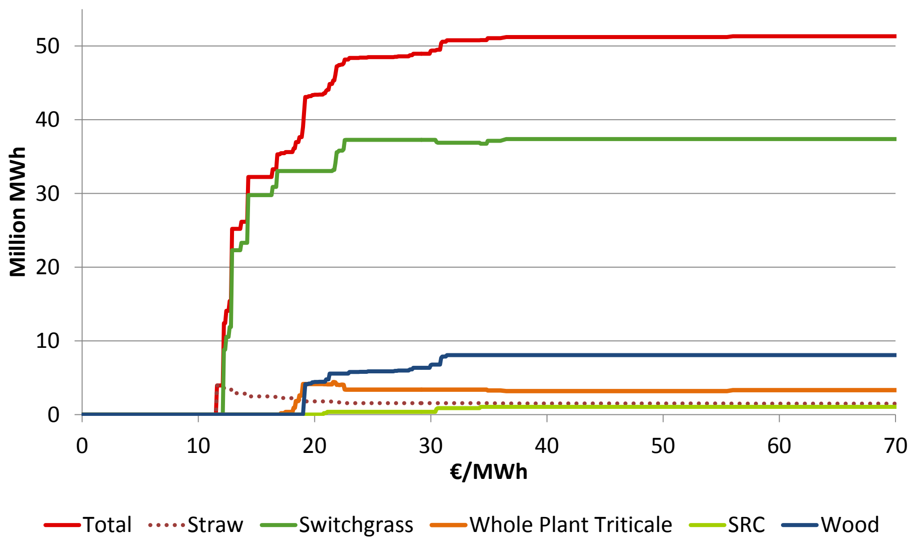


Fig. 1.10. Detail of the lignocellulosic biomass mix supplied in the benchmark case.

those presented in the section "individual supply curves". That is to say, the first and cheapest biomass source is straw, for it is a by-product of cereal crops in the model and is given a production cost only worth its fertilising value. It is quickly followed by Switchgrass for a minimum price of 12.2 €/MWh, whose supply reaches a plateau for prices over 22.6 €/MWh. Whole plant triticale is grown and supplied for prices over 17.1 €/MWh, though it is less profitable than Switchgrass. This is explained by the validation constraints: they impose areas in sugar beets and potatoes and these crops are included in crop rotations in which whole plant triticale can be substituted for barley. Validation contraints also explain the fact that perennial crops are limited to 66% of the regional UAA. Most surprisingly, Switchgrass is not the only perennial crop supplied as poplar SRC is provided for minimum prices of 20.8 €/MWh. Despite higher energy yields per hectare, SRC is less profitable than switchgrass because it has higher fixed establishment costs. However, this only holds true until prices reach 30.6€/MWh. In that case, SRC is substituted for Switchgrass, but only to a certain extent because agropedoclimatic conditions restrict areas suitable for cultivating SRC.

Perennial lignocellulosic crops are commonly expected to be grown on the less fertile agricultural land and thus not in competition with food crops. However, our results show that it is not the case, at least in the Champagne-Ardenne region, where Switchgrass and Miscanthus have the highest yields on SARs 4 to 6, which are among the most fertile and profitable SARs for food crops. Fig. 1.11 shows that they are not grown at first on the least fertile and profitable areas [6].

Though decreasing on average in the Champagne-Ardenne region, the number of pesticides and herbicides treatments can increase in some SARs for some price ranges (see figures 1.12 and 1.13 respectively) due to indirect land use change in the region. E.g., the average number of treatments per hectare increases for MWh prices ranging from 12.4 to 18.6 €/MWh in SAR3, which corresponds to a rotation substitution leading to a decrease in alfalfa area and an increase in wheat, rapeseed and beetroot area, the latter being more treated.

Impact of the agricultural price economic context

The agricultural price context impacts the minimum price for which lignocellulosic biomass is supplied in the case of low prices (9.5 €/MWh instead of 11.6€/MWh). It also impacts the amount of biomass supplied for a given price, until a threshold of 58 €/MWh for which an identical maximum amount of 51,310,813.5 MWh is reached (c.f. Fig. 1.9). The agricultural price context has an impact on the biomass supply location, as far as

[6] SAR1 and SAR2 are the least profitable areas for food crops, SAR6 and SAR7 are intermediate and SAR3 to 5 are the most profitable

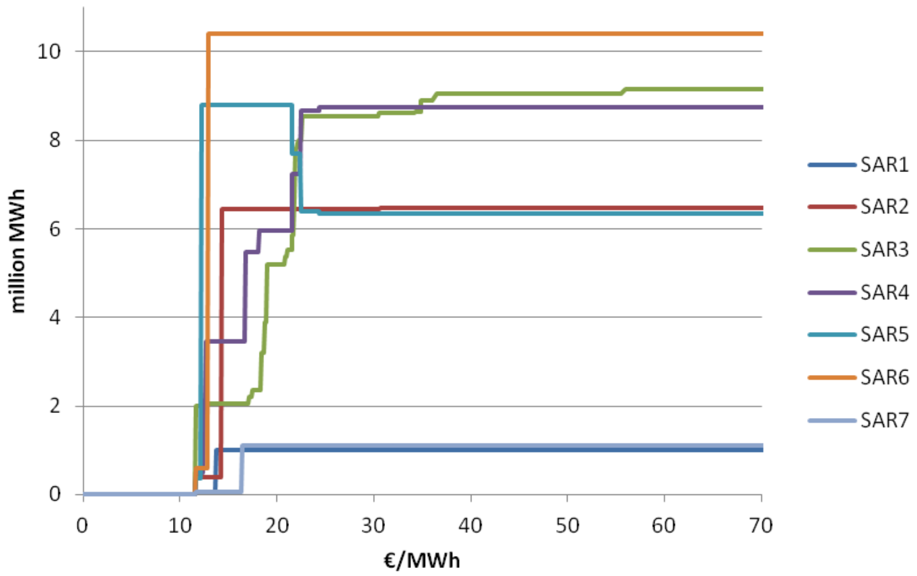


Fig. 1.11. Detail of the amount of biomass supplied by each Small Agricultural Regions in the benchmark case (in million MWh).

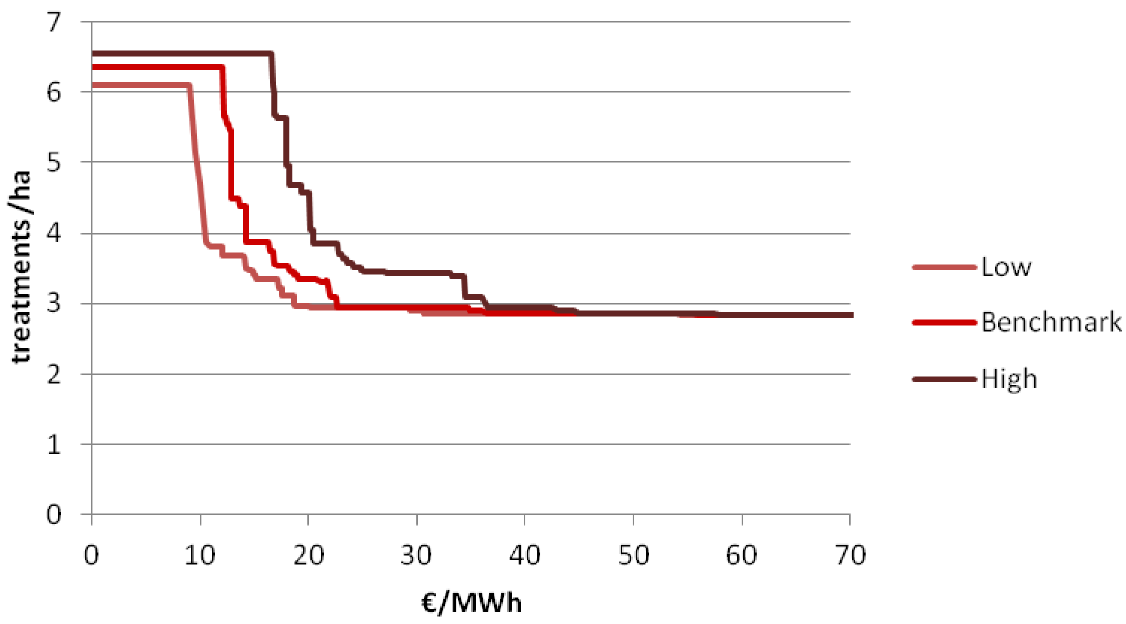


Fig. 1.12. Average number of pesticides and herbicides treatments per hectare in the region, depending on the agricultural prices context.

SARs are concerned, especially in the high price context (see figures 1.19a and 1.19b in appendix). Details on the biomass mix composition are provided in appendix in figures 1.20a and 1.20b.

The opportunity costs of the first MWh provided for each biomass source is generally

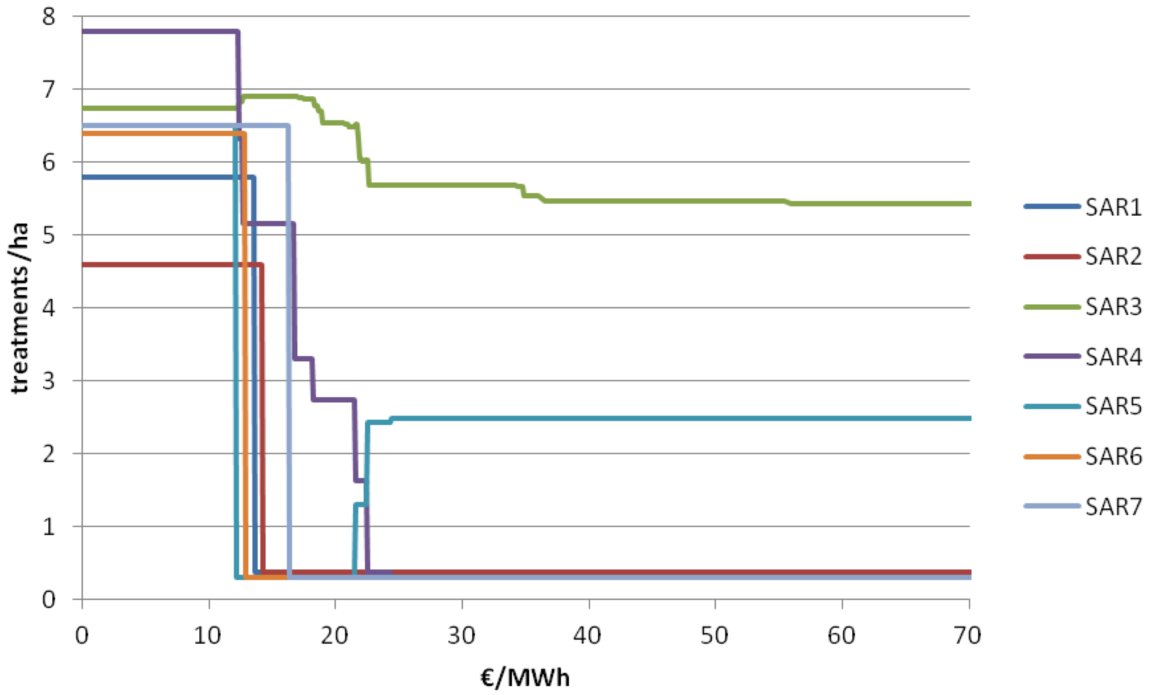


Fig. 1.13. Average number of pesticides and herbicides treatments per hectare in each Small Agricultural Regions, in the benchmark case.

higher when there is competition between the biomass sources (c.f. Table 1.12 in comparison with Table 1.10). However, except for whole plant triticale and SRC in the high price context, biomass sources have the same order of appearance.

1.4.3 Bioenergy facility siting

Comparing the results for a facility's demand for biomass equivalent to 2 728 612 MWh with the results from the previous subsection for the same demand level, enables us to investigate the impact of facility location on the choice of biomass to be grown, the supply cost, and the potential environmental impacts. The facility's demand represent circa 5.3% of the total amount of lignocellulosic biomass that can be supplied by the region, based on Section 1.4.2.

Benchmark case

In the benchmark case, the facility is located in county 5110 and is supplied with 362 763 oven dry tons of straw (39% of the total exportable straw in the region) and 261 876 oven dry tons of switchgrass silage. Switchgrass silage comes from the county where the facility is located and straw comes from 29 different counties (see figure 1.15). The

	Low	Benchmark	High
Cereal Straw	11.6	11.6	11.6
Switchgrass	9.5	12.2	16.7
Whole plant Triticale	13.9	17.1	23.2
Miscanthus	*	*	*
Fiber Sorghum	*	*	*
Poplar SRC 12	19.2	20.8	26.6
Poplar SRC 10	30.5	30.5	33.2
Poplar SRC 8	*	*	*
Softwood	19.1	19.1	19.1
Hardwood	19	19	19
Poplar	24.6	24.6	24.6

Table 1.12
Opportunity costs of the first MWh equivalent of each type of biomass entering the biomass mix produced in the region, depending on the agricultural price context (in euro/MWh with a precision of 0.1 euro).

opportunity cost of the last MWh of biomass delivered to the facility (i.e., switchgrass from SAR4) is 12.703€/MWh and includes a 5.167 € production and conditioning cost, 7.5€ of foregone revenue due to crop rotation substitution, and a 0.036€ intra-county transportation cost.

Based on the regional supply curve (Section 1.4.2), the opportunity cost of supplying 2 728 612 MWh is 11.511 €/MWh in the benchmark case. The biomass mix is composed only of straw bales (654 343 tons, i.e., 69% of the total exportable straw) supplied by 82 counties and mainly from SAR3 (see figure 1.14). The level of pesticide and herbicide treatments (figure 1.16b) as well as nitrogen fertilisation (figure 1.17b) remain the same compared to a situation without biomass supply (figure 1.16c and figure 1.17c respectively).

When facility siting and transportation are accounted for, the composition of the biomass mix is modified, the dedicated biomass production is concentrated in fewer counties, and its opportunity cost increases. Biomass is supplied from fewer SARs (3-4-5-7), and mainly from SAR4 and SAR3. The nitrogen fertilisation level increases slightly whereas the number of treatments decreases slightly, on average at the region level (see figures 1.17a and 1.16a for maps). However, at the local level, the average fertilisation and herbicide and pesticide treatments levels increase for some counties.

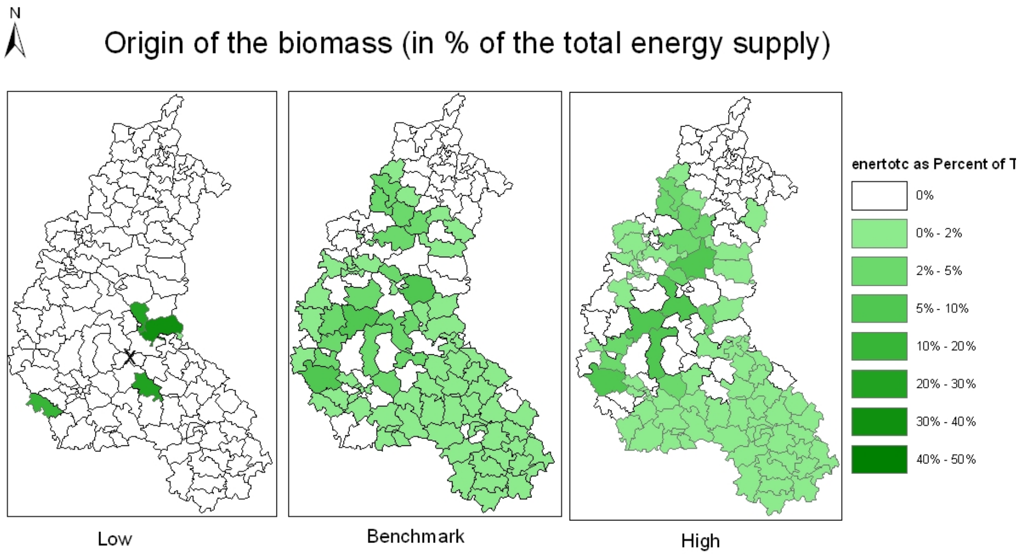


Fig. 1.14. Biomass supply per county for the various agricultural prices scenarios ("low", "benchmark", and "high") when there is no facility to be located (in percentage of total supply in primary energy content).

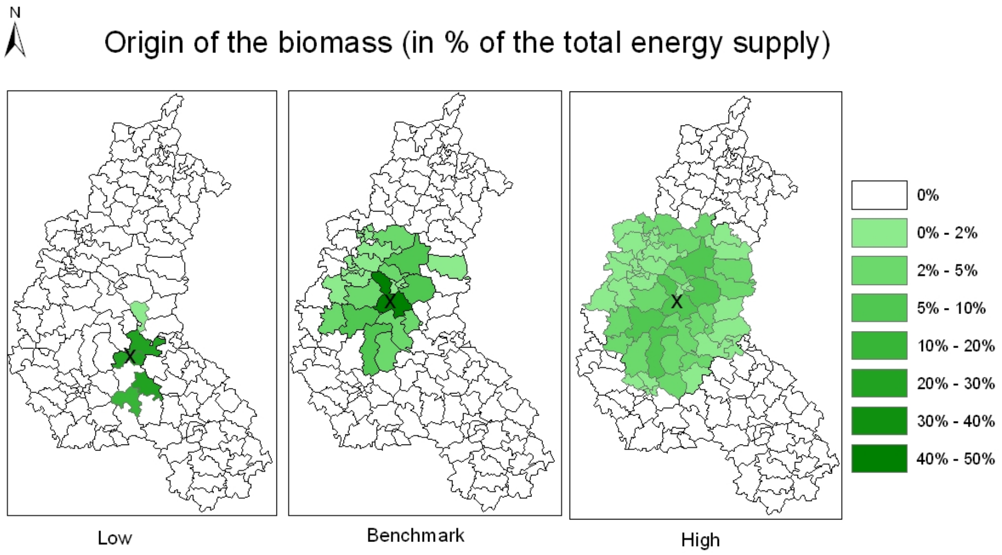
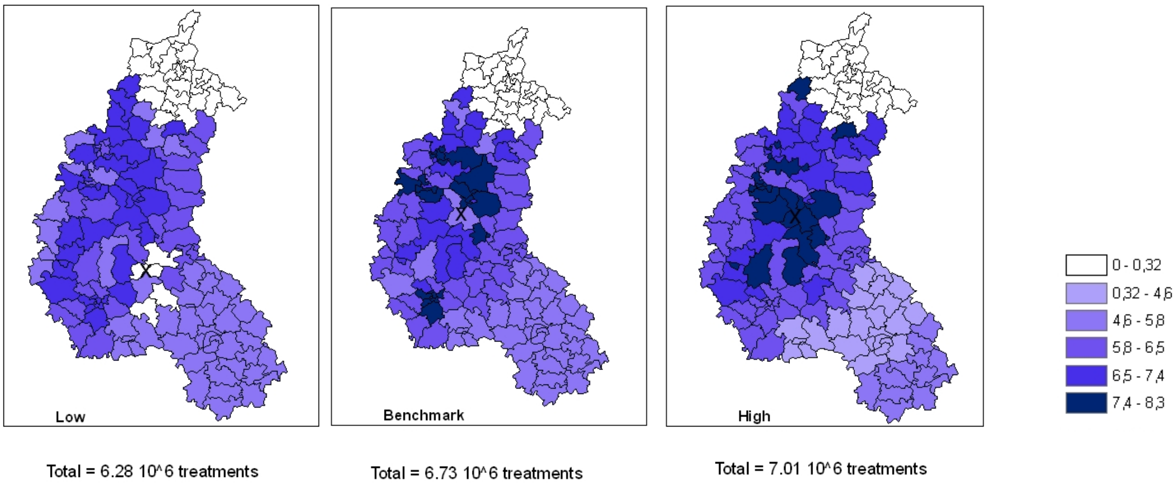
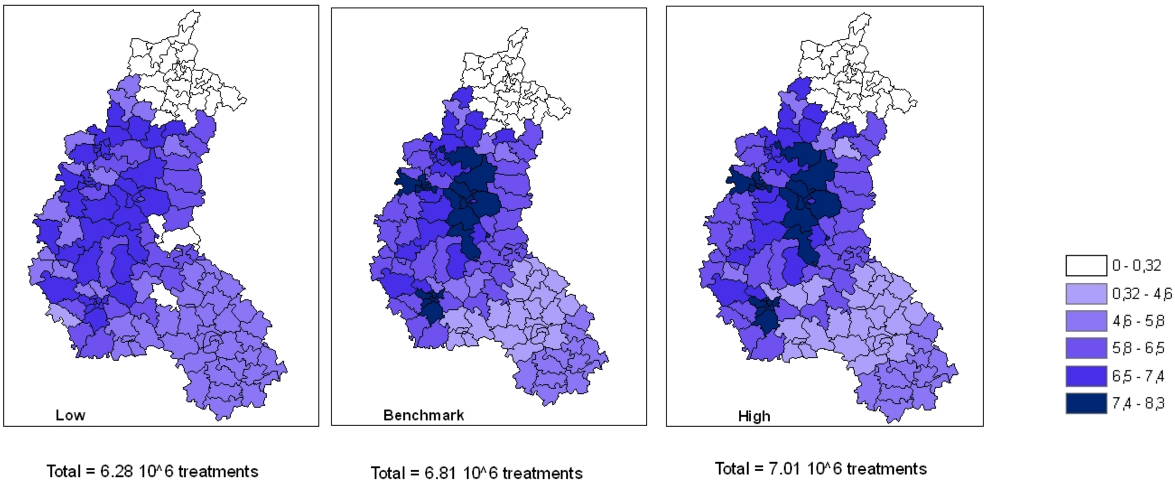


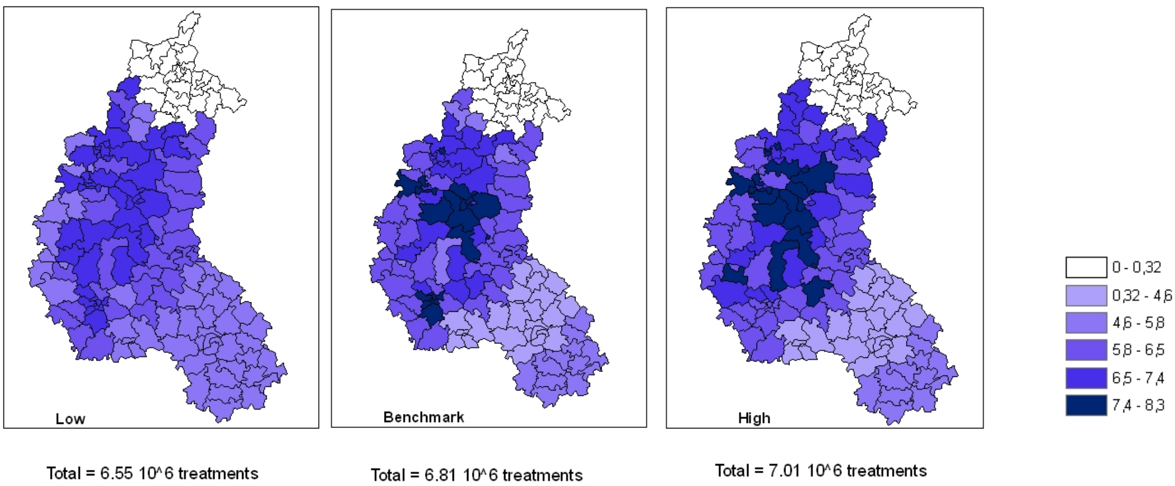
Fig. 1.15. Facility location (X) and biomass supply per county (percentage of total supply in primary energy content) for the various agricultural prices scenarios : "low", "benchmark", and "high".



(a)



(b)



(c)

Fig. 1.16. Average number of herbicide and pesticide treatments per county (in treatments /ha) depending on the agricultural price context ("low", "benchmark", "high") for three scenarios : **(a)** biomass demand with facility location, **(b)** biomass demand with no facility, **(c)** no biomass demand.

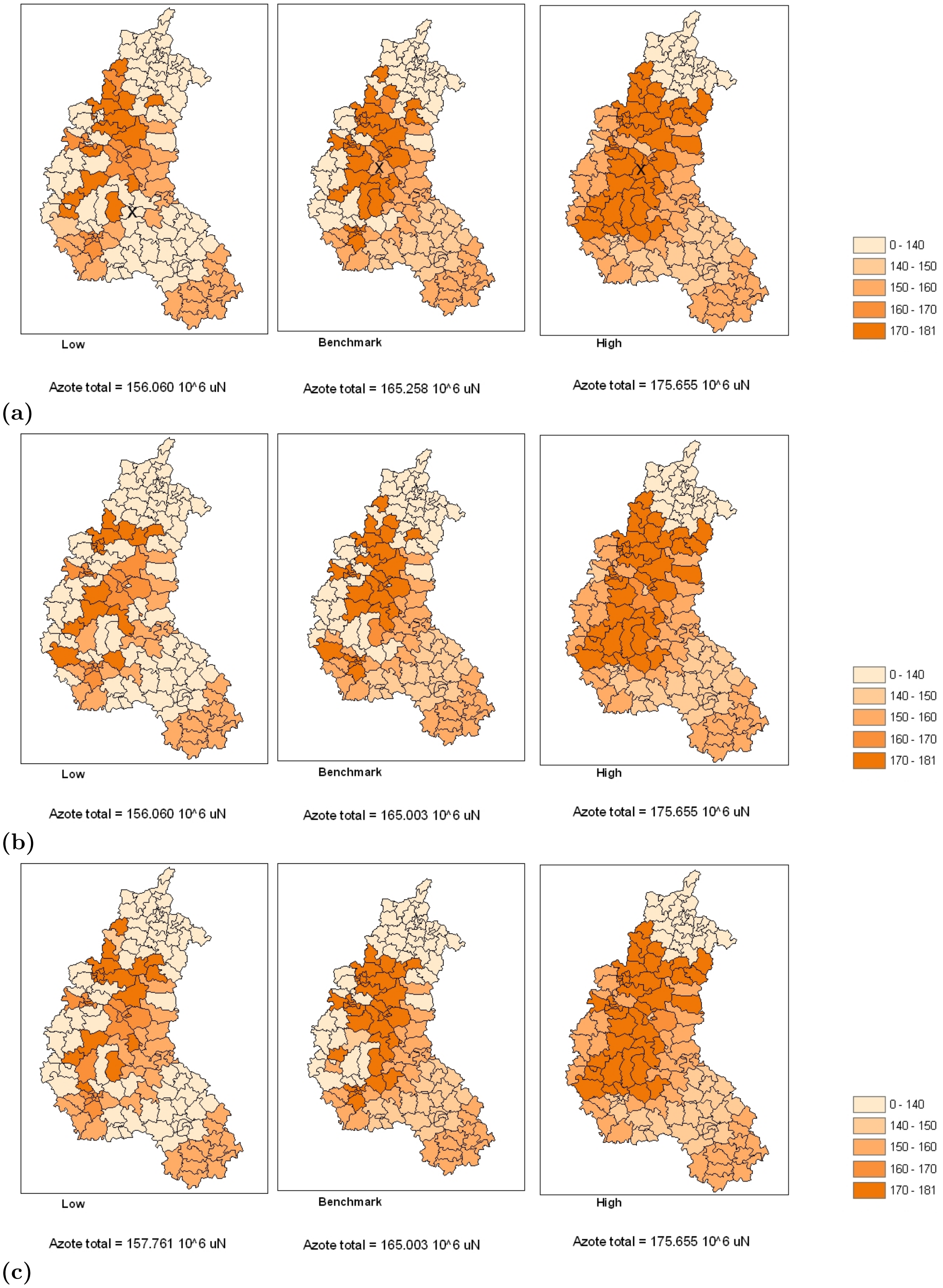


Fig. 1.17. Average nitrogen fertilisation level per county (in N units /ha) depending on the agricultural price context ("low", "benchmark", "high") for three scenarios : **(a)** biomass demand with facility location, **(b)** biomass demand with no facility, **(c)** no biomass demand.

Impact of the "Low" agricultural prices economic context

In the case of "low" agricultural prices, the facility is located in another county "1008" and is supplied with 587 683 o.d. tons of switchgrass silage, arriving from 5 different counties belonging to SAR6 (see figure 1.15). The opportunity cost of the last MWh of biomass delivered to the facility (i.e., switchgrass from county 5133) is 11.055 €/Mwh and includes a 5.778 € production and conditioning cost, 3.52€ of foregone revenue due to crop rotation substitution, and a 1.757€ transportation cost to the facility.

Based on the regional supply curve, the opportunity cost of supplying 2 728 612 MWh is 9.299 €/MWh in the low price context case. The biomass mix is composed only of silage Switchgrass (587 683 tons dry matter) supplied by 5 counties belonging to SAR6. The number of pesticide and herbicide treatments (figure 1.16b) as well as the nitrogen fertilisation level (figure 1.17b) decrease in the region, compared to a situation without biomass supply (figure 1.16c and figure 1.17c respectively).

When facility siting and transportation are accounted for, the composition of the biomass mix remains the same. However, though still belonging to SAR6, the producing counties differ. In addition, the opportunity cost of the switchgrass supplied increases. The nitrogen fertilisation level and the number of treatments remain the same on average at the region level (see figures 1.17a and 1.16a for maps). However, at the local level, the average fertilisation and herbicide and pesticide treatments levels increase for some counties.

Impact of the "high" agricultural prices economic context

In the case of "high" agricultural prices, the facility is still located in county "5110", but is only supplied with straw (654,343 o.d. tons) arriving from 53 different counties (see figure 1.15). Straw is mainly harvested on SAR3 and represent 66% of the total amount of exportable straw in the region. The opportunity cost of the last MWh of straw delivered to the facility is 13.028 €/Mwh and includes a 11.51 € production and conditioning cost and a 1.517€ transportation cost to the facility.

Based on the regional supply curve, the opportunity cost of supplying 2 728 612 MWh is 11.511 €/MWh in the high price context case. The biomass mix is composed only of straw bales (654343 tons, i.e., 66% of the total exportable straw) supplied by 80 counties and mainly from SAR3. The level of pesticide and herbicide treatments (figure 1.16b) as well as nitrogen fertilisation (figure 1.17b) are the same compared to a situation without biomass supply (figure 1.16c and figure 1.17c respectively).

When facility siting and transportation are accounted for, the composition of the biomass mix remains the same, the dedicated biomass production is concentrated in fewer counties, and its opportunity cost increases. Biomass is supplied from less SARs (3-4-5-6-7), though still mainly from SAR3. The nitrogen fertilisation level and the number of treatments remain the same on average at the region level (see figures 1.17a and 1.16a for maps). However, at the local level, the average fertilisation and herbicide and pesticide treatments levels increase for some counties.

1.5 Conclusion and Discussion

Within an overall project to assess the competitiveness and environmental impacts of the production of bioenergy from lignocellulosic biomass, we set out in this particular study to investigate facility location, land allocation, biomass supply costs, and some environmental impacts in relation to the demand for lignocellulosic feedstock at the regional (Nuts 2) level.

For that purpose we developed a spatially-explicit regional supply model with a county sub-level to deal with the case of agricultural and forest lignocellulosic biomass. It accounts for land-use competition, transportation costs and the optimal location of bioenergy facilities as well as the competition between biomass sources and between their potential uses.

To illustrate our approach, we applied the model to the case of the French Champagne-Ardenne region. We generated the first lignocellulosic biomass supply curves for France and examined the type, quantity, opportunity cost and location of the biomass supplied, depending on the food crops price context.

Our results show that the Champagne-Ardenne region can provide up to 51.3 million MWh equivalent of lignocellulosic biomass, for a maximum opportunity cost of 58 euro/MWh [7]. The regional biomass mix is mainly composed of Switchgrass and to a lesser extent wood. This confirms that in this region dedicated energy crops can contribute to biomass production for bioenergy uses.

In addition, our results show that dedicated crop cultivation can increase environmental pressure on the local level, due to direct and indirect land-use substitution. We assessed the level of pesticide and herbicide as well as nitrogen fertiliser use at the county, Small Agricultural Region (SAR), and region levels. Although dedicated crop cultivation tend to decrease their use on average at the region level, it is not always the case at the county or SAR level. This can occur due to direct land use change because some

[7]Most of this maximum biomass supply is reached around 25 euros/MWh

dedicated crops have higher input levels than the crops to which they substitute. For instance whole plant triticale is more fertilised than barley, to which it substitutes in crop rotations. Or when the demand for straw increases, rotations with a higher share of cereal crops substitute to other, less input-intensive, rotations. Increased environmental pressure can also occur due to indirect land use change, when dedicated crop cultivation modify the location of other crops. In our study, it is the case for sugar beet and potatoe for instance, because we impose constraints on their area at the *département* level to reflect the fact that these crops are generally subjected to quotas and/or contracts.

Facility location has an impact on the type, cost and location of the biomass supplied, due to tradeoffs between "farm gate" supply costs and transportation costs. Compared to the same non-spatialised demand, facility location concentrates lignocellulosic feedstock production in fewer couties. Moreover, we show that foregone revenues incurred by land-use substitution play a major role in the supply cost of dedicated lignocellulosic crops. This clearly emphasizes the importance of accounting for land-use competition and substitution to accurately address the sustainability (competitiveness and environmental impacts) of lignocellulosic biomass production.

Our results also show that three well-accepted claims about the production and supply of lignocellulosic biomass in France do not hold true countrywide. First, although Miscanthus is the most frequent dedicated perenial crop in France today, it is not the most profitable dedicated crop in the Champagne-Ardenne region. We have found that Switchgrass has lower opportunity costs, a finding consistent with a study carried out by Bocquého and Jacquet (2010). Second, perennial lignocellulosic crops are commonly expected to be grown on less fertile agricultural land, thereby not coming into competition with food crops. However, our results show that this is not the case in Champagne-Ardenne where they would be at first grown in counties with the most fertile and profitable lands and not on marginal land. Switchgrass and Miscanthus actually have the highest yields on soil types which are the most fertile and profitable ones for food crops too. Finally, it is expected that forest remnants, which are not currently exploited, will be massively used for energy purposes. However, we show that remnants are not the providential biomass source they are expected to be. In fact, remnants are used if and only if prices are high enough to make them profitable. Therefore, energy and non-energy uses will continue to compete for wood that is harvested.

1.6 Perspectives

Our approach could undergo further development. First, the modeling of necessary logistics could be refined. Due to the huge volumes of biomass to be transported and the need to supply the facility all year long, the scheduling of biomass collection and storage play an important role in the competitiveness of lignocellulosic bioenergy chains. Second, surveys on the willingness of producers (farmers, forest owners and managers) to offer biomass were carried out in the framework of the project (ARVALIS/ONIDOL, 2009b; FCBA, 2009). Looking to avoid mass production of new crops in a given county, it would be interesting to integrate these results to better account for the behaviour of producers.

By using such a methodology, we should be able to more accurately predict the contribution of the agricultural and forest sectors to the potential biomass supply, and to provide investors and policy makers with insights into how best to envision the contribution of lignocellulosic biomass to renewable energy projects.

The presented methodology also constitutes a good basis to further investigate the environmental impacts of lignocellulosic biomass production and supply, in relation to its spatial distribution. These impacts are, for instance, variations in nitrogen fertilisation, greenhouse gas emissions linked to the biomass production and delivery, or the impacts of land-use changes on landscape and biodiversity. Moreover this spatially explicit approach could serve as a means to improve bioenergy production life cycle analyses (LCAs[8]). Since such an approach provides crucial information on the production side, i.e., on soils, cropping practices and especially land-use changes, it is expected that it will allow us to carry out consequential LCAs.

By further investigating the environmental impacts of biomass production and supply, in an integrated modelling framework, we will be able to determine if there is a need for public policies to mobilize this biomass potential in an environmentally-friendly way. If yes, this modelling framework will help us design the appropriate policies.

[8]First LCAs for the test region were performed during the project, see Gabrielle (2009)

1.A Appendix Model equations

$$\max_{X_i, LBD_{i,j}, (locus_j)} \sum_i \left(\Pi_i^{CROPS}\left(S_i^{ROT}\right) + \Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right) + \right.$$
$$\left. + \Pi_i^{ENERGY}\left(X_i^{ENERGY}\right)\right) - \sum_{i,j} T_{i,j}^{ENERGY}\left(LBD_{i,j}^{ENERGY}\right) \cdot locus_j \tag{1.20}$$

subject to

$$\sum_{r,s} S_{r,s,i}^{ROT} \leq UAA_i, \quad \forall i \tag{1.21}$$

$$X_{c,s,i}^{CROPS} = \sum_r \left(y_{c,s} \cdot \gamma_{c,r} \cdot S_{r,s,i}^{ROT}\right), \quad \forall c, s, i \tag{1.22}$$

$$X_i^{EStraw} \leq \sum_{r,s} \left(\alpha_i \cdot y_{c,i}^{straw} \gamma_{c,r} \cdot S_{r,s,i}^{ROT}\right), \quad \forall i \tag{1.23}$$

$$W_i^{WOOD} \leq \overline{W_i^{WOOD}}, \quad \forall i \tag{1.24}$$

$$\rho \cdot \left(X_i^{NEWood} + X_i^{EWood}\right) \leq W_i^{WOOD}, \quad \forall i \tag{1.25}$$

$$X_i^{ECrop} + X_i^{EWood} + X_i^{EStraw} = X_i^{ENERGY}, \quad \forall i \tag{1.26}$$

$$X_i^{ENERGY} \geq \sum_j LBD_{i,j}^{ENERGY}, \quad \forall i \tag{1.27}$$

$$\sum_i LBD_{i,j}^{ENERGY} \cdot lhv^{ENERGY} = D^{ENERGY} \cdot locus_j, \quad \forall j \tag{1.28}$$

$$W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood} \geq 0, \quad \forall i \tag{1.29}$$

$$S_{r,s,i}^{ROT} \geq 0, \quad \forall r, s, i \tag{1.30}$$

$$LBD_{i,j}^{ENERGY} \geq 0, \quad \forall i, j \tag{1.31}$$

Constraint 1.21 sets that the areas grown with rotations including food and/or energy crops must be less than the total agricultural area in each county. Constraint 1.22 links crops production to the area dedicated to the various crop rotations. Constraint 1.23 relates the amount of straw that can be used for energy purpose to the area grown with cereal crops, and limits it to the share that can be exported without harming the soil organic matter content. Constraint 1.24 and 1.25 limits the amount of wood that is harvested for energy and non-energy uses to the amount available annually. We assume here that agricultural and forest areas are independent, i.e., deforestation and afforestation are not allowed, and that short rotation coppices (SRC) can only be grown on agricultural areas.

The lignocellulosic feedstock supply in each county X_i^{ENERGY} equals the sum of its annual and perennial dedicated crops X_i^{ECrop}, cereal straw X_i^{EStraw}, and wood X_i^{EWood} supply (1.26). A county i cannot export more lignocellulosic feedstock to other counties j than its own production (1.27). The total amount of lignocellulosic biomass delivered to a county j must satisfy the facility's demand, if it exists (i.e. $locus_j = 1$) (Equation (1.28)).

Agricultural biomass equations

$$\Pi_i^{CROPS}\left(S_i^{ROT}\right) = \sum_{c,s}\left(\left(p_c \cdot y_{c,s} - c_{c,s}^{prod}\right) \cdot \sum_r \gamma_{c,r} \cdot S_{r,s,i}^{ROT}\right) \tag{1.32}$$

$$\Pi_i^{ENERGY}\left(X_i^{ECrop}\right) = \sum_c \left(\left(p^{MWh} \cdot lhv_c - c_c^{cond}\right) \cdot X_{c,i}^{ECrop}\right) \tag{1.33}$$

$$\Pi_i^{ENERGY}\left(X_i^{EStraw}\right) = \left(p^{MWh} \cdot lhv_{straw} - c_{straw}^{cond}\right) \cdot X_i^{EStraw} \tag{1.34}$$

Forest biomass equations

$$\begin{aligned}\Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right) = \sum_{w,cond}\left(p^{wood} \cdot X_{w,cond,i}^{NEWood}\right) - \\ - \sum_{w,cond}\left(c_{w,cond}^{stump} \cdot W_{w,cond,i}^{WOOD} + c_{w,cond}^{harv} \cdot \left(X_{w,cond,i}^{NEWood} + X_{w,cond,i}^{EWood}\right)\right)\end{aligned} \tag{1.35}$$

$$\Pi_i^{ENERGY}\left(X_i^{EWood}\right) = \sum_w p^{MWh} \cdot lhv_w \cdot X_{w,i}^{EWood} \tag{1.36}$$

Agricultural and woody biomass transportation equations

$$T_{i,j}^{ECrops}\left(LBD_{c,i,j}^{ECrops}\right) = \sum_{c,cond,vcl}\left(t_{c,cond,vcl,i,j} \cdot LBD_{c,cond,vcl,i,j}^{ECrops}\right) \tag{1.37}$$

with :

$$t_{c,cond,vcl,i,j}^{ECrop} = \delta_{c,cond,vcl,cld} \cdot d_{i,j} + \epsilon_{c,cond,vcl,cld} \tag{1.38}$$

and cld being the distance class to which belong $d_{i,j}$; $\delta_{c,cond,vcl,cld}$ and $\epsilon_{c,cond,vcl,cld}$ being the parameters of the dedicated crops transportation cost function (in €/km and €, respectively).

$$T_{i,j}^{EWood}\left(LBD_{w,i,j}^{EWood}\right) = \sum_{w,cond,vcl}\left(t_{w,cond,vcl,i,j}^{EWood} \cdot LBD_{c,cond,vcl,i,j}^{EWood}\right) \tag{1.39}$$

with :

$$t^{EWood}_{w,cond,vcl,i,j} = \vartheta^{EWood}_{c,cond,vcl} \cdot d^2_{i,j} + \delta^{EWood}_{c,cond,vcl} \cdot d_{i,j} + \epsilon^{EWood}_{w,cond,vcl} \tag{1.40}$$

and $\vartheta^{EWood}_{c,cond,vcl}$, $\delta^{EWood}_{c,cond,vcl}$, and $\epsilon^{EWood}_{w,cond,vcl}$ being the parameters of the quadratic transportation cost function for wood (in €/km^2, €/km, an € respectively.

1.A.1 Nomenclature

Name	Definition
Indices	
i, j	departure and arrival counties
c	crops, including dedicated crops
cld	distance class
$cond$	types of conditionning for the lignocellulosic biomass
r	crops rotations
s	soil types
vcl	vehicle types
w	woody biomass types

Table 1.13

Name	Definition	Unit
Variables		
$LBD_{i,j}^{ENERGY}$	amount of lignocellulosic biomass (energy crop, straw or wood) delivered to county j from county i	(tons)
$LBD_{c,i,j}^{ECrop}$	amount of energy crop delivered to county j from county i	(tons)
$LBD_{i,j}^{EStraw}$	amount of energy straw delivered to county j from county i	(tons)
$LBD_{w,i,j}^{EWood}$	amount of woody biomass of type w delivered to county j from county i	(tons)
$locus_j$	binary variable is equal to 1 if a bioenergy facility is located in county j and to 0 otherwise	
$S_{r,s,i}^{ROT}$	area of rotation r grown on soil s in county i	(ha)
$X_{c,s,i}^{CROPS}$	quantity of crop c (energy or non-energy crop) produced in county i on soil s	(tons)
X_i^{ENERGY}	total energy feedstock supply of county i	tons
X_i^{ECrop}	annual and perennial dedicated crops supply of county i	tons
X_i^{EStraw}	amount of straw devoted to energy use in county i	(tons)
X_i^{EWood}	amount of wood devoted to energy use	tons
X_i^{NEWood}	amount of wood devoted to non-energy use	tons
W_i^{WOOD}	wood volume of trees to be cut	m^3

Table 1.14

Name	Definition	Unit
Parameters		
α_i	Share of straw that can be exported from the county without harming its soil organic matter content	
$\gamma_{c,r}$	Share of crop c in crop rotation r	
$c_{c,s}^{prod}$	crop c production cost on soil s	€/ha
c_c^{cond}	energy crops conditionning cost	€/ton
c_{straw}^{cond}	straw conditionning cost	€/ton
$c_{w,cond}^{harv}$	harvest cost per type of woody biomass and conditionning	€/ton
$c_{w,cond}^{stump}$	stumpage per wood type and conditionning	€/m^3
$d_{i,j}$	distance between counties	km
D^{ENERGY}	exogenously given demand of a facility for lignocellulosic biomass	(MWh eq.)
lhv^{ENERGY}	energy content (lower heating value) of lignocellulosic biomass (energy crop, straw, or wood)	(MWh/ton)
lhv_c	energy content (lower heating value) of crop c	(MWh/ton)
lhv_{straw}	energy content (lower heating value) of straw	(MWh/ton)
lhv_w	energy content (lower heating value) of woody biomass	(MWh/ton)
p_c	crop price	€/ton
p^{MWh}	energy feedstock price / lignocellulosic biomass price	€/MWh
ρ	density of wood	$(tons/m^3)$
$t_{c,cond,vcl,i,j}$	energy crops transportation cost	€/ton
$t_{w,cond,vcl,i,j}^{EWood}$	wood transportation cost	€/ton
UAA_i	total utilised agricultural area available in county i	(ha)
$\overline{W_i^{WOOD}}$	maximum volume of wood that can be harvested annually in county i	m^3
$y_{c,s}$	Yield of crop c grown on soil s	(ton/ha)
$y_{c,i}^{straw}$	Yield of straw from cereal crops	ton/ha

Table 1.15

1.B Appendix Case study

tab:Data sources Details on data sources and processing as well as data providers for the models' parameters are summarized in the following table (see table1.16).

Table 1.16 Details on data sources and processing.

Parameters	Comments	Sources
Agricultural data		
Aggregated Small Agricultural Regions	GIE Arvalis-ONIDOL aggregated the 27 SARs of the region (INSEE classification) into 8 groups and linked each county to one of these groups.	ECOBIOM project
Agricultural and fodder areas per county	Based on year 2005 farmers declaration for CAP subsidies. Aggregated at the county level for cash crop farms on the one hand and for bredding and dairy farms on the other hand.	ONIGC (French Interprofessional Office of Crop Farming) (purchased by Arvalis)
Permanent grassland areas	They were estimated for cash crop farms at the département level, based on SAA 2007 PG areas and the share of PG areas located in farm types 13 and 14 (enquête structure 2007, stru 005). We then assumed that these permanent grassland areas are uniformly distributed within the counties belonging to a given département.	SAA 2007,enquête structure 2007
Existing crops and crop rotations	Based on a survey of local experts by Arvalis. The three main rotation patterns in te regions were identified by local Arvalis experts.	Arvalis, regional extension officers (CRA), and Rural Economic Centers (CER), (ARVALIS, 2007)

Continued on next page

Table 1.16	continued from previous page	
Parameters	Comments	Sources
Food crops yields, production costs and prices.	Yields and production costs are averages over a 10-year period (1997-2007). Food crops prices provided for years 1993 to 2007.	CERs (Centres d'Economie Rurale) of départements de l'Aube and Haute-Marne,(ARVALIS, 2007) .
Food crops price scenarios	The three price scenarios (mean, 1^st, and 9^th decile of the 1993-2007 prices were kindly computed and provided by C. Gouel (INRA).	
Dedicated crops yields and production costs	Based on first results from field trials	REGIX research project[9], (ARVALIS/ONIDOL, 2009a).
Poplar SRC data	The potential production areas for each of the 3 types of poplar SRC were obtained by overlaying soil, land use and county borders maps, following a methodology developped in the framework of the VALERBIO project	FCBA
Input use data	Information on the amount of nitrogen fertilizer, the number of pesticides and herbicides treatments, and fuel consumption, per crop and small agricultural region.	Arvalis, FCBA

Continued on next page

[9]REGIX was funded by the French National Research Agency (ANR, Agence Nationale de la Recherche) under the National Research Programme on Bioenergy (PNRB, Programme National de Recherche sur les Bioénergies) and coordinated by F. Labalette, GIE Arvalis-Onidol.

Table 1.16 continued from previous page

Parameters	Comments	Sources
Forest data		
Forest features	Forest stands maps and departemental statistics	IFN (French National Forest Survey)
	Stands' slopes	IGN
	Distance from plots to the nearest road	SERFOB (Service Régional de la FOrêt et du Bois)
Net annual harvestable wood volume per county	Computed by FCBA from IFN, IGN and SERFOB data, accounting for harvesting losses, wood volumes that are unharvestable due to technical logging difficulties or to the reluctance of small private owners.	FCBA
Harvesting costs, stumpage and wood prices	They were provided for Champagne-Ardenne by the French Association of Forest Cooperatives (Union des Coopératives Forestières de France, UCFF) and were harmonised with those from the French National Forestry Service (Office National des Forêts, ONF)	UCFF, ONF .

Continued on next page

Table 1.16	continued from previous page	
Parameters	Comments	Sources
Transportation data		
Distance data	Kindly provided by M. Hilal	Distancier Intercommunal Route 500, INRA UMR 1041, CESAER, Dijon, France.
Transportation costs	Based on the CNR 2008 trinomial formula, adapted by FCBA for wood and by Arvalis for crops.	FCBA, Arvalis, CNR.

1.B.1 Agricultural data

The composition of the various crop rotations included in the model as well as their compatibility with the various Small Agricultural Regions are provided in tables 1.17 to 1.20.

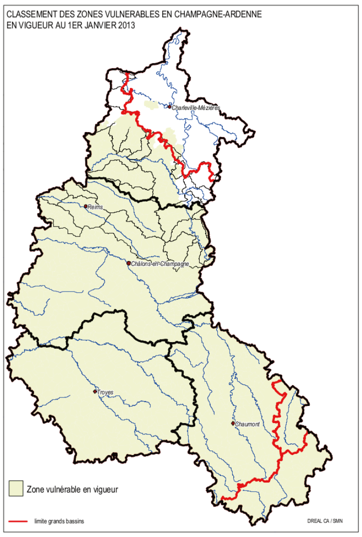


Fig. 1.18. Map of the Nitrates Directive "vulnerable zones" in 2013 for the Champagne-Ardenne region.

	ROT1	ROT2	ROT3	ROT4	ROT5	ROT10	ROT11	ROT12	ROT32
	rapeseed wheat barleyW	rapeseed wheat barleyW peaS wheat/gpc	rapeseed wheat barleyS	rapeseed wheat barleyS sugar beet wheat	maize wheat wheat/w sunflower wheat	maize wheat peaS wheat/gpc	rapeseed wheat wheat/w barleyW	rapeseed wheat wheat/w sugar beet wheat	maize wheat wheat/w rapeseed wheat
	ROT1	ROT2	ROT3	ROT4	ROT5	ROT10	ROT11	ROT12	ROT32
SAR1			1		1				1
SAR2	1	1	1		1	1	1		1
SAR3	1	1	1	1	1	1	1	1	1
SAR4	1	1	1	1	1	1	1	1	1
SAR5	1	1	1	1	1	1	1	1	1
SAR6	1	1	1		1	1	1		1
SAR7	1	1	1		1	1	1		1

Table 1.17
Food crop rotations and their compatibility with the Small Agricultural Regions (part1)

	ROT6	ROT7	ROT8	ROT9	ROT34	ROT35	ROT36	ROT37
	alfalfa1	alfalfa1	alfalfa1	horsebean pea	rapeseed	rapeseed	rapeseed	rapeseed
	alfalfa2	alfalfa2	alfalfa2	wheat/gpc	wheat	wheat	wheat	wheat
	alfalfa3	alfalfa3	alfalfa3	barleyW	wheat/w	wheat/w	barleyW	barleyW
	wheat/gpc	wheat/gpc	wheat/gpc	rapeseed	sunflower	sunflower	peaS	peaS
	wheat/w	wheat/w	barleyW	wheat	wheat	wheat	wheat/gpc	wheat/gpc
	sunflower	sunflower	rapeseed	barleyS	potatoeS	potatoeF	potatoeF	potatoeS
	wheat	wheat	wheat	peaW	wheat/gpc	wheat/gpc	wheat/gpc	wheat/gpc
	barleyW	barleyW	barleyS					
	potatoeF	potatoeS	maize					
	wheat/gpc	wheat/gpc	wheat					
	ROT6	ROT7	ROT8	ROT9	ROT34	ROT35	ROT36	ROT37
SAR1								
SAR2				1				
SAR3	1	1	1	1	1	1	1	1
SAR4				1	1	1	1	1
SAR5	1	1	1	1	1	1	1	1
SAR6				1				
SAR7				1				

Table 1.18
Food crop rotations and their compatibility with the Small Agricultural Regions (part2)

ROT13	ROT14	ROT28	ROT29	ROT30	ROT31
sugar beet	sugar beet	sugar beet	sugar beet	sugar beet	sugar beet
barleyS	wheat	wheat	wheat	wheat	wheat
rapeseed	rapeseed	barleyS	barleyS	barleyS	barleyS
wheat	wheat	rapeseed	rapeseed	rapeseed	rapeseed
barleyW	barleyW	wheat	wheat	wheat	wheat
alfalfa1	alfalfa1	barleyW	barleyW	sugar beet	sugar beet
alfalfa2	alfalfa2	potatoeF	potatoeS	wheat	wheat
alfalfa3	alfalfa3	wheat/gpc	wheat/gpc	barleyW	barleyW
wheat/gpc	wheat/gpc			potatoeF	potatoeS
barleyS	barleyS			wheat/gpc	wheat/gpc
potatoeF	potatoeS				
wheat/gpc	wheat/gpc				

	ROT13	ROT14	ROT28	ROT29	ROT30	ROT31
SAR1						
SAR2						
SAR3	1	1	1	1	1	1
SAR4			1	1	1	1
SAR5	1	1	1	1	1	1
SAR6						
SAR7						

Table 1.19
Food crop rotations and their compatibility with the Small Agricultural Regions (part3)

	ROT16	ROT17	ROT18	ROT19	ROT20	ROT21	ROT22	ROT23	ROT24
	miscanthus	switchgrass	rapeseed wheat triticaleWP	rapeseed wheat triticaleWP sugar beet wheat	rapeseed wheat triticaleWP peaS wheat/gpc	alfalfa1 alfalfa2 alfalfa3 wheat/gpc barleyW rapeseed wheat triticaleWP maize wheat	sorghumF wheat peaS wheat/gpc	sorghumF wheat wheat/w sunflower wheat	alfalfa1 alfalfa2 alfalfa3 wheat/gpc barleyW rapeseed wheat barleyS sorghumF wheat
	ROT16	ROT17	ROT18	ROT19	ROT20	ROT21	ROT22	ROT23	ROT24
SAR1	1	1	1		1				
SAR2	1	1	1		1		1	1	
SAR3	1	1	1	1	1	1	1	1	1
SAR4	1	1	1	1	1		1	1	
SAR5	1	1	1	1	1	1	1	1	1
SAR6	1	1	1		1		1	1	
SAR7	1	1	1		1		1	1	

Table 1.20
Energy crop rotations and their compatibility with the Small Agricultural Regions.

1.B.2 Forest data

Here we provide examples of harvesting costs and stumpage.

		Very easy	Easy	Difficult	Very difficult
Big	Non-barked logs	13.3	16.7	18.9	22.2
	Long-barked logs	17	20	20	23
	Short-barked logs	19	22	23	26
	Wood chips	24	28	28	32
Medium	Long-barked logs	17	20	20	23
	Short-barked logs	19	22	23	26
	Wood chips	24	28	28	32
Small	Bundles	20		23	
	Wood chips	30	34	40	44

Table 1.21
Example of wood harvesting costs for softwood from old trees, depending on wood diameter, wood conditioning, and logging difficulty level (in €/ fresh ton).

		Non-barked logs	Long-barked logs	Short-barked logs	Bundles	Wood chips
Softwood	Big	52.222	15	17.273		11
	Medium		15	17.273		9
	Small				3	3
Poplar	Big	33	9.5			11
	Medium		9.5			9
	Small				3	3
Hardwood	Big	49.412	15			11
	Medium		15			9
	Small				3	3

Table 1.22
Stumpage depending on the species, wood diameter, and conditioning (in €/ fresh ton).

			$\delta_{c,cond,vcl,cld}$						$\epsilon_{c,cond,vcl,cld}$
Crop	Conditionning	Vehicle	cld0-25	cld25-50	cld50-100	cld100-150	cld150-200	cld200+	cld0
Straw	bale	cr5	0.153	0.104	0.087	0.081	0.087	0.076	0.076
triticaleWP	bale	cr5	0.153	0.104	0.087	0.081	0.087	0.076	0.076
miscanthus	bale	cr5	0.168	0.114	0.095	0.089	0.095	0.083	0.084
switchgrass	bale	cr5	0.179	0.122	0.102	0.095	0.102	0.089	0.090
miscanthus	silage	srb	0.273	0.187	0.157	0.147	0.157	0.137	0.137
triticaleWP	silage	srb	0.294	0.201	0.169	0.158	0.169	0.148	0.147
switchgrass	silage	srb	0.336	0.230	0.193	0.180	0.193	0.169	0.168
sorghumF	silage	srb	0.392	0.268	0.225	0.210	0.225	0.197	0.196
triticaleWP	silage	multib	0.306	0.208	0.174	0.162	0.174	0.152	0.153
miscanthus	silage	multib	0.312	0.212	0.177	0.165	0.177	0.155	0.156
switchgrass	silage	multib	0.383	0.260	0.218	0.203	0.218	0.190	0.191
sorghumF	silage	multib	0.515	0.351	0.293	0.274	0.293	0.256	0.258

Table 1.23
Coefficients of the transportation costs linear function for each distance interval (in €/ton/km), depending on the crop, its conditionning and the type of vehicle that is used (cr5 = camion remorque 5 essieux; srb = semi remorque avec benne; multib= multibenne). Source : Arvalis, based on the French National Road Center trinomial formula.

1.B.3 Transportation costs

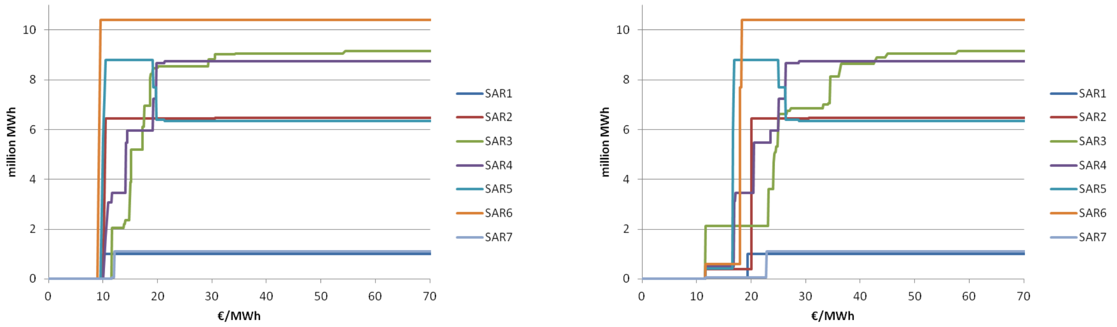
Agricultural biomass transportation costs, in form of piecewise linear functions per distance interval.

Woody biomass transportation costs, in form of quadratic functions of the distance .

Conditioning	Vehicle	$\vartheta^{EWood}_{c,cond,vcl}$	$\delta^{EWood}_{c,cond,vcl}$	$\epsilon^{EWood}_{w,cond,vcl}$
Logs	sr5	-0.00004	0.0444	7.2317
Logs	cr6g	-0.00004	0.0484	7.4646
Logs	sr6g	-0.00004	0.0492	7.058
Bundles	sr5	-0.00005	0.0555	9.0396
Bundles	sr6g	-0.00005	0.0636	9.1165
Wood chips	fma	-0.00004	0.0477	8.6335
Wood chips	polyb	-0.00006	0.0663	10.376

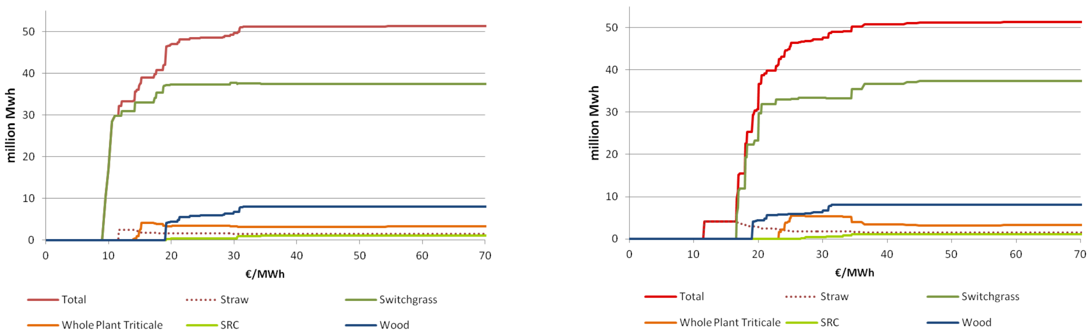
Table 1.24
Coefficients of the woody biomass transportation cost functions, depending on the biomass conditoning and type of vehicle(in €/fresh ton/km^2 , €/fresh ton/km, and €/fresh ton respectively). sr5 = semi remorque 5 essieux; cr6g = camion remorque 6 essieux avec grue; sr6g = semi remorque 6 essieux avec grue; fma = fond mouvant; polyb = poly-bennes. Source: FCBA, based on the French National Road Center trinomial formula.

1.C Appendix Results



(a) (b)

Fig. 1.19. Detail of the amount of biomass supplied by each Small Agricultural Regions in the low and high prices context s(in million MWh).



(a) (b)

Fig. 1.20. Detail of the lignocellulosic biomass mix supplied in the low and high prices context (in millions MWh).

Chapter 2

Stochastic viability of second generation biofuel chains: Micro-economic spatial modeling in France

Abstract

To better understand the production of biofuels derived from lignocellulosic feedstock, we investigate the interplay between the agricultural sector and a biofuel facility, at the local level. More specifically, what is the economic and technological viability of a bioenergy facility over time in an uncertain economic context? The stochastic viability approach is applied. Two viability constraints are taken into consideration: the facility's demand for lignocellulosic feedstock has to be satisfied each year and the associated supply cost has to be lower than the facility's profitability threshold. We assess the viability probability of various strategies the facility can adopt to ensure that the agricultural sector meets its demand for biomass. Referred to here as supplying strategies, they vary according to what percentage of the total demand will be met by contracting out the demand to farmers who are growing perennial crops. Determined at the initial time, the percentage varies from 0 to 100%. Supplies for any remaining demand will come from annual crops or wood. The demand constraints and agricultural price scenarios over the time horizon are introduced in an agricultural and forest biomass supply model, which in turns determines the supply cost per unit of energy and computes the viability probabilities of the supplying strategies. A sensitivity analysis to agricultural prices at the initial time is performed. If a facility is to be viable over time, it is best for it

to ensure that 100% of its demand is contracted out to farmers supplying perennial dedicated crops. This result is robust to the price context.

2.1 Introduction

In a global context of efforts to reduce greenhouse gases emissions and to achieve energy independence, renewable energy sources (including biofuels and bioliquids) are presented as an alternative to fossil fuels. The European Union has set mandatory targets for 2020 for the share of energy from renewable sources in overall energy consumption in the Union, and for energy related to transport for each Member State, at 20% and 10%, respectively.[1] The European Commission has also emphasized the importance to produce renewable energy sources locally (e.g., to achieve supply security, employment and rural development opportunities) and in compliance with sustainability criteria. In this context, biomass is expected to play an important role : it is renewable, can be cultivated in all regions, converted into heat, electricity or biofuel, and stored in huge quantities. It is important to determine to what extent the agriculture and the forestry sectors could contribute to the production of bioenergy at both global and regional scales, in a sustainable way.

This issue has been addressed in several large scale studies that examine the potential global production (for a survey, see Berndes et al., 2003; EEA, 2006; Ericsson and Nilsson, 2006), which generally do not consider the economic conditions required for this production. Determining these conditions requires detailed modeling of the supply side, such as that in Rozakis and Sourie (2005) which examines the supply of first generation biofuels in France using a detailed micro-economic model of the agriculture sector to determine the profitability of the biofuel chain in an uncertain economic context.

The first generation of biofuels, however, is subject to sustainability concerns (Scarlat and Dallemand, 2011) since it competes with food production, potentially leading to increases in food prices (Zilberman et al., 2013), and appears less promising in relation to its environmental benefits as initially envisaged (Searchinger et al., 2008). Lignocellulosic biomass generally has higher energy content and yield for lower input levels; thus, the second generation of biofuels (based on cellulosic and lignocellulosic biomass, which includes agricultural and woody biomass) is advocated as being more compatible with the objectives of sustainable agricultural development.

[1]Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

However, there are problems related to this second generation of biofuels : the emergence of a lignocellulosic biofuels supply chain may prove difficult. Babcock et al. (2011) examine the market conditions for the emergence of a competitive cellulosic biofuel sector and show that sector competitiveness depends on both the institutional context (subsidies) and the competition with the traditional ethanol chain. They emphasize that the feedstock price is a key driver of the production cost of second generation biofuels, this price being determined locally because biomass transportation costs are high with respect to the value of the biomass and there is no existing market for cellulosic biofuel feedstock. However, their study does not consider the local feedstock supply, while forecasts on the contribution of biomass to future global energy supply vary widely with assumptions about land availability and yield levels (Berndes et al., 2003), and delivery costs are an important factor of profitability (Graham et al., 2000). Hellmann and Verburg (2011) use an aggregate top-down approach to assess European production possibilities. However, assessing the profitability of production facilities requires accounting for the local context, along with uncertainty about the prices of agricultural commodities and, thus, about the opportunity cost of local cellulosic feedstock.

Ballarin et al. (2011) adopt a weighted goal programming model to assess the trade-offs between farmers' incomes and potential bioenergy production at the regional level, accounting for the local environmental and agronomic context, but without explicitly considering either the production facilities or the uncertainty in agricultural commodity prices, which would influence the actual production of bioenergy. Kocoloski et al. (2011) employ a mixed integer programming model to define the optimal location of cellulosic ethanol refineries at the U.S. level. Focusing on transportation costs, they show that ethanol production costs vary with the local availability of biomass, which emphasizes the role of the location of cellulosic ethanol facilities on their profitability. Their study accounts for the response of biomass supply to the feedstock price and competition over land-use with other commodities, but does not model explicitly the local price formation for cellulosic biofuel feedstock or the influence of price fluctuations in other commodities on supply costs and quantities. Methods and applications are thus missing to assess the local conditions for regional lignocellulosic bioenergy chains to emerge and, in particular, to examine the viability of bioenergy facilities in terms of biomass supply and supply cost.

In this paper, we examine the economic and technological viability of a bioenergy facility in an uncertain economic context, in terms of both the capacity to supply the facility with biomass of a quality consistent with the production under consideration, and in terms of associated supply costs. We apply a stochastic viability approach (De Lara and Martinet, 2009; Doyen and De Lara, 2010). In dynamic systems under uncertainty, this approach ranks management strategies with respect to the probability that they generate a trajectory of the system that respects a set of constraints over time. We consider a lignocellulosic bioenergy production facility that needs to define a supplying strategy for its input biomass. The facility has two viability constraints. On the one hand, it needs sufficient annual quantity of biomass to sustain energy production. On the other hand, the associated supply cost has to be lower than a threshold representing the facility's profitability price. Since this profitability threshold may depend on the type of facility, we provide a sensitivity analysis of this constraint level. We assess the viability probability of various supplying strategies based on the proportion of contracted perennial crops, i.e., the probability with which these strategies make it possible to respect the constraints over time in a stochastic context for agricultural commodity prices.

To describe the local agricultural context, we use a spatially explicit regional supply model for agricultural and forest lignocellulosic biomass. This model gives the response of production to fluctuating market prices as well as the composition, origin, and cost of the supplied biomass. The model is not specific to a given technology. The methodology is general, but for illustrative purposes it is applied to the enzymatic hydrolysis and fermentation technology (to produce bioethanol from lignocellulosic biomass), using data for the Champagne-Ardenne region (France) over a fifteen years time period.

The paper is structured as follows. Section 2.2 describes the methodology and modeling approach. Section 2.3 describes the case-study and introduces the scenarios. Section 2.4 analyzes the numerical results and Section 2.5 provides a discussion and conclusions.

2.2 Methodology

The methodology is aimed at defining i) the viability probability of various supplying strategies for the biomass supply of lignocellulosic bioenergy chains, ii) the associated supplying cost, and iii) the spatial origin and the type of biomass.

2.2.1 The stochastic viability approach

Adopting the viewpoint of a lignocellulosic bioenergy facility, we look for the supplying strategies that maximize the technological and economic viability of the facility, under price uncertainty. For this purpose, we use the stochastic viability approach (De Lara and

Martinet, 2009; Doyen and De Lara, 2010). The viability approach consists in examining the consistency of a dynamic system with a set of so-called viability constraints, i.e., in determining if it is possible to satisfy the constraints over time, starting from a given initial state of the system (Aubin, 1991). In the stochastic framework, the probability of respecting these constraints over time is used to rank strategies.

We consider two viability constraints: i) the facility's demand for lignocellulosic feedstock D (in primary energy equivalent of adequate biomass) has to be satisfied each year; and ii) the associated supply cost (mean cost per unit of input energy) has to be lower than a threshold $\bar{P}$ representing the profitability of the process.

The facility's supplying strategies consist in contracting a share of the feedstock demand to perennial dedicated crops, Q_0^{pc}, at the initial time $t = 0$ for a contractual price P_0^{pc}. This quantity is then supplied at this price each year over the planning horizon. The remaining demand is then met by annual dedicated crops or wood, Q_t^{ac}, at a price P_t^{ac} that depends on the market conditions that year.

The two viability constraints read as

$$Q_t^{ac} + Q_0^{pc} \geq D, \tag{2.1}$$

and

$$\frac{P_t^{ac} Q_t^{ac} + Q_0^{pc} Q_0^{pc}}{Q_t^{ac} + Q_0^{pc}} \leq \bar{P}. \tag{2.2}$$

The facility is said to be technologically and economically viable when these constraints are satisfied at all periods over the planning horizon. We rank the supplying strategies with respect to their probability to satisfy both constraints at all time periods, over the planning horizon. We assume that the supplying strategies vary according to the share of total demand met by contracting out the demand to farmers who are growing perennial crops. Here, uncertainty is related to the supply price of annual biomass, P_t^{ac}, which depends on exogenous shocks on agricultural prices (global price context) and on the supplying strategy (local biomass price formation).

The profitability threshold (maximal cost of supply) of a given plant depends on its technology and the output price. As our model is not restricted to a particular type of cellulosic bioenergy facility, we treat this maximal cost $\bar{P}$ as a parameter and perform a sensitivity analysis on its value.[2]

From a technical point of view, this viability probability can be approximated by a frequency using Monte-Carlo simulations, by simulating a large number of agricultural

[2]Moreover, the actual profitability threshold of a given facility is a private and strategic information that is not easy to assess.

price scenarios (one such being a sequences of prices for all commodities over the planning horizon) and examining the success frequency of each strategy across these scenarios. This approach requires us to model the response of regional agricultural production to prices. Price scenarios are generated using a stochastic agricultural price model. The demand constraints, strategies and agricultural prices scenarios are introduced in an agricultural and forest biomass supply model, which, in turn, determines the mean supply cost per unit of energy and computes the viability probabilities of the various supplying strategies.

2.2.2 The modeling framework

We aim at modeling the dynamic land-use of an agricultural region to determine the quantities produced in response to local market incentives for biomass supply and global market incentives for other commodities. The model must in particular define the local biomass price.

We consider an agricultural region where land use maximizes farmers' gross margins. Farmers are price takers for non-energy commodity prices, in the sense that local production does not affect the price of these commodities. At the beginning of year t, anticipated prices for these agricultural outputs are formulated with respect to past observed agricultural commodity prices. At the same time, the region faces a demand for biomass from a bioenergy production facility. This demand, in primary energy equivalent, is given and is supposed non-flexible. The local market for lignocellulosic biomass sets a price for biomass supply, and land allocation and commodity production are then defined to maximize the region's total gross margin.

For simplicity, to determine the price of local biomass we assume the following. A unit of biomass will be produced and delivered to the plant if the local price is higher than the foregone revenue from the best agricultural production alternative plus biomass production and delivery costs. Thus, the local market is cleared at a price that equals the opportunity cost of the last unit of biomass delivered to the bioenergy production plant.

Modeling the global economic context: Stochastic price scenarios

Uncertainty in our application is related to stochastic commodity prices. A scenario is a sequence of prices for all commodities (except biomass traded on the regional market) over the 15-year planning horizon.

We assume that market prices for commodities can be represented as a VAR process.[3]

[3] A VAR model makes it possible to represent the serial correlation (Deaton and Laroque, 1992) and

The price level equation is

$$p_t = A + Bt + Cp_{t-1} + u_t, \tag{2.3}$$

where p_t is the vector of the logarithm of prices; A and B are the coefficient vectors of exogenous variables: a constant and a trend; C is the coefficient matrix; u_t is the error term, with $\mathrm{E}(u_t) = 0$ and $\mathrm{E}(u_t u_t') = \Sigma_u$.

The time series available for local prices are too short to estimate a VAR on annual prices. Since primary commodity markets are well integrated internationally, in our estimation we use the international commodity price indexes provided by Grilli and Yang (1988) and updated by Pfaffenzeller et al. (2007). Prices are annual and extend from 1900 to 2003. They are deflated by the United Nations Manufactures Unit Value index. We use price information on corn, palm oil, wheat, and timber. We consider them as reference prices for all the other commodities.

The estimation results are presented in Table 2.1. They show that prices have a positive first order correlation, a behavior that can be related to the effect of storage, which tends to smooth shocks over several periods (Deaton and Laroque, 1992). It implies that a period of low (high) prices is most likely to be followed by low (high) prices. Lagged effects of one commodity over another are limited. Nonetheless, prices move together because of common contemporaneous shocks, as shown by the covariance matrix of residuals.

	Wheat	Corn	Palm oil	Timber
time	−0.003*	−0.005**	−0.002	0.003**
Wheat(−1)	0.566***	−0.061	0.018	−0.011
Corn(−1)	0.108	0.560***	0.285**	0.065
Palm oil(−1)	0.051	0.153	0.560***	0.009
Timber(−1)	0.017	0.077	0.022	0.736***
R^2	0.828	0.803	0.818	0.877
Covariance matrix of residuals:				
Wheat	0.024			
Corn	0.019	0.039		
Palm oil	0.006	0.016	0.042	
Timber	0.005	0.007	0.012	0.016

Notes: The constant is omitted in the results. *, ** and *** denote significance at the 10%, 5% and 1% level.

Table 2.1
VAR estimates of commodity prices dynamics

the co-movement of commodity prices (Pindyck and Rotemberg, 1990; Ai et al., 2006). We follow Beck (2001) by introducing a time trend that accounts for the effect of productivity change or demand change on prices.

We use this estimation to simulate potential price trajectories, by drawing shocks from a centered multivariate normal distribution of covariance matrix Σ_u. We remove the time trend and rescale the equations by multiplying them by the average of 15-year Champagne-Ardennes prices and dividing them by their estimated price means.

In addition to the simulated prices, we calculate the corresponding conditional expectations, which are used to endow farmers with rational expectations of next period prices. We consider that, at the regional level, farmers are price taker for marketed commodities, i.e., the local production does not affect global prices, and take their land-use decisions as based on expected prices depending on past observations. This results in a sequence of locally anticipated price series, which represent uncertainty scenarios for the bioenergy facility.

As the production of perennial cellulosic crops requires a long-run commitment from farmers, it depends on the opportunity cost of alternative crops at the initial year. We consider three different price contexts in which the initial agricultural prices are set to different values. In the benchmark scenario the initial prices are equal to the mean prices for 1993–2007. In the "low prices" scenario agricultural prices start from values equal to the 1$^{\text{st}}$ decile of the 1993–2007 prices. Correspondingly, the "high prices" scenario corresponds to the 9$^{\text{th}}$ decile of the 1993–2007 prices.

An example of a simulated price path starting from a high price situation is illustrated in Fig. 2.1. In addition to the simulated prices (plain line), price expectations are represented in two variants: next-year expected price (dashed-line), $\mathrm{E}_{t-1}(P_t)$, on which farmers base their land allocation for annual crops, and t-year ahead expected price (dotted-line), $\mathrm{E}_0(P_t)$, which is the relevant price for the farmers' supply strategy. Notice that this latter price converges to its long-run average, what illustrates the mean-reversal aspect of the price dynamics.

Modelling the regional biomass supply and associated costs

To assess the supplying costs of the bioenergy facility as well as the spatial origin and the type of biomass, we use a spatially explicit regional supply model for agricultural and forest lignocellulosic biomass. It accounts for two spatial levels: county and region.

The county is the smallest administrative (sub)level for which data are available. In our model, the county is the spatial level at which production decisions occur, taking account of technical and economic constraints. Each county is characterized by its soil composition, altitude, and the slope of forest stands. It is the elementary unit for locating biomass departure and delivery points. We denote the number of counties by A and the

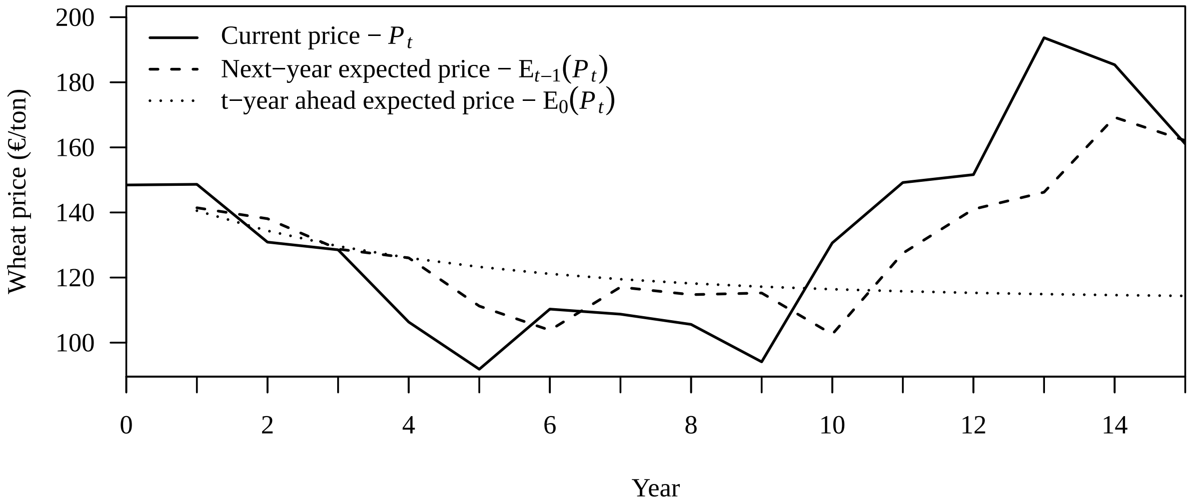


Fig. 2.1. Example of a simulated "high price" scenario

number of agricultural commodities by I. Decision variables at county level are the area devoted to each commodity for field crops[4] and the harvested wood quantities per category for forest.[5] The area devoted to the production of commodity i in county a is denoted by $X_{i,a}$. For simplicity, we denote the land use of county a by the compact expression X_a. Production is characterized by the biomass and crop yields and production costs, as well as available wood quantities per category and related stumpage and harvesting costs. The production and production cost functions of commodity i in county a depend on the land use X_a in that county and are denoted by $Q_{i,a}(X_a)$ and $C_{i,a}(X_a)$.

The region is the relevant level when it comes to drawing the boundaries of the biomass supply area and studying the competition for resources that arises when a bioenergy facility is being set up. It is the level at which distances and transportation costs from counties to the bioenergy facility are accounted for. The type, quantity, and conditioning of biomass supplied to the bioenergy facility are determined optimally at the regional level.[6] At initial time $t = 0$, the facility contracts out dedicated perennial crops at the contractual price P_0^{pc} to meet a part γ of its demand D according to the supplying strategy.[7] The corresponding areas in perennial crops are then removed from production in each county for the rest of the planning horizon. The remaining area of county a is

[4]Formally, the model considers crop rotations, which means that there are (agronomic) constraints linking the areas devoted to each commodity.

[5]In what follows, for the sake of clarity, we omit the time subscript.

[6]The biomass delivered to the plant is not always to be used as it is and may require a pre-treatment (e.g., drying or chipping), inducing an extra cost that could change the optimal biomass supply. This could be easily included in our model if the technology of the facility is specified.

[7]See below how this price and the supplying conditions (type, quantity, and origin of the biomass) are determined.

denoted by L_a. The share of demand that is not supplied by contracted perennial crops has to be supplied by annual dedicated crops or wood. The annual demand for biomass is expressed in primary energy equivalent and is denoted by $(1-\gamma)D$. It depends on the considered supplying strategy. The quantity of commodity i supplied to the bioenergy facility by county a is denoted by $S_{i,a}$. Its lower heating value is denoted by ρ_i. The associated transportation cost function is denoted by $T_{i,a}(S_{i,a})$. We consider that farmers take their land-use decisions using expected prices, as described above. The expected price for commodity i is denoted by P_i. The local market for biomass is defined so as to supply the demand $(1-\gamma)D$ to the facility at the lowest possible cost.

We use a mathematical programming model to maximize the region's agricultural and forestry income, considering the various potential uses of biomass (food, energy, industry or timber). Here, we present a stylized version of the model, treating all commodities the same way.[8] The optimization problem is as follows:[9]

$$\max_{\{X_{i,a}\geq 0, S_{i,a}\geq 0\}} \sum_{a=1}^{A}\sum_{i=1}^{I}\left\{P_i\left[Q_{i,a}\left(X_a\right)-S_{i,a}\right]-C_{i,a}\left(X_a\right)-T_{i,a}\left(S_{i,a}\right)\right\}, \tag{2.4}$$

subject to

$$L_a-\sum_{i=1}^{I}X_{i,a}\geq 0, \quad \forall a \tag{2.5}$$

$$\sum_{a=1}^{A}\sum_{i=1}^{I}S_{i,a}\rho_i-(1-\gamma)D\geq 0, \tag{2.6}$$

$$Q_{i,a}(X_a)-S_{i,a}\geq 0, \quad \forall i,a \tag{2.7}$$

Constraints (2.5) represent the land availability in all counties. Constraint (2.6) represents the market condition to meet the technological viability constraint (biomass demand). The dual value of the demand constraint (2.6) is the opportunity cost of the last energy unit delivered to the facility, i.e., the foregone revenue of the best production alternative plus biomass production and shipping costs. It provides the purchase price of annual feedstock, P_t^{ac}.

We use this model to determine the optimal land use and assess the opportunity cost of biomass.[10] The model is used recursively to determine the intertemporal optimal land

[8]Forest areas are actually independent from agricultural areas and wood products are described with quantities rather than with surfaces in the model.

[9]This model is a linear programming model as the location of the biomass processing plant is given. It is written in GAMS and solved with the CPLEX solver.

[10]To determine the nature, quantity and origin of contracted biomass, we ran the same model with an additional constraint on dedicated perennial crops, so that a quantity γD is supplied by these crops.

use, the quality and origin of the annual biomass delivered to the lignocellulosic bioenergy facility, and the related opportunity cost, P_t^{ac}. For each simulation scenario, the total biomass supply cost is computed each year following equation (2.2) and is compared to the economic profitability threshold of the facility.

2.3 Case study

As a case study, we consider a second generation ethanol production facility setting-up in the French Champagne-Ardenne region. This agricultural and forested region includes 146 counties with both agricultural and forestry activities. Different types of lignocellulosic crops can be grown there and R&D activities in the field of second generation biofuels are established in the area. The facility uses enzymatic hydrolysis and fermentation to produce bioethanol from lignocellulosic biomass, with a target production of 180 million liters of ethanol per year. This corresponds to the case of a project under study in the region. Considering the current process energy efficiency of 0.39 (Schmidt et al., 2010) and a 7000 hours/year workload hypothesis, this implies a biomass input of 389.8 MW/year. The optimal location of the facility was determined in Bamière (2013).

2.3.1 Model data and assumptions

We assume here that: i) agricultural and forest areas are independent, i.e., deforestation and afforestation are not allowed; ii) short rotation coppices (SRC) can only be grown on agricultural areas; iii) all biomass is available at the county seat. We account only for the agricultural area of crop farms.[11]

Soil and agricultural data. We account for 7 soil types. Based on their agropedoclimatic characteristics, counties can grow 13 conventional crops and 5 dedicated crops: miscanthus, switchgrass, whole-plant triticale, fiber sorghum, and poplar SRC. Crops are combined into 33 crop rotations, among which 9 contain dedicated crops, plus poplar SRC. Crop rotations allow accounting for the preceding and following crop effects on yields, input consumptions (e.g. nitrogen balance) and environmental impacts. Moreover, considering rotations facilitates comparison of crop rotations (composed of annual crops) to perennial crops such as miscanthus, switchgrass, and SRC. We assume that farmers will substitute perennial crops for existing crop rotations, and that annual dedicated crops

[11]Types of Farming 13 and 14 in accordance with the Farm Accountancy Data Network classification.

will likely substitute to equivalent crops in crop rotations (whole-plant triticale substitutes to barley, and fiber sorghum to maize). For conventional crops, regional data were collected to compute average yields and production costs over the period 1997–2007.[12] The yields of dedicated crops are estimated based on the first results from field trials.[13] The associated production costs for perennial crops are used to compute an equivalent annual cost (with a 5% discount rate) over the whole rotation duration. Dedicated crops can be conditioned into silage or high density bales.

Forest data. The annual wood volume available to harvesting per county depends on the characteristics of the existing forests (area, location, ownership, species, age of trees and slope of plots). It was computed by the French Technological Institute for Forest, Cellulosis, and Building lumber (FCBA) based on three main data sources.[14] For the Champagne-Ardenne region there are 60 harvested wood categories and 5 types of conditioning (non-barked logs, long barked logs, short barked logs, bundles, and woodchips). Harvesting costs (including felling cost, tree processing, and hauling costs), stumpage (the price paid by an operator to the land owner to harvest the standing timber on his land) as well as wood prices for the region were provided by the French Association of Forest Cooperatives and harmonized with the French National Forestry Service data.

Transportation data. We use the distances that minimize transportation time.[15] Transportation costs per metric ton and kilometer are calculated using the trinomial formula from the "French National Road Center" (Centre National Routier, CNR), based on kilometric costs, hourly rates, and fixed costs as well as the type of vehicle used.[16]

2.3.2 Validation

To validate our model, we compare the simulated regional land use to the observed 2007 situation in Champagne-Ardenne. The validation scenario entails maximizing the sum of

[12] Arvalis, cropping surveys made by Rural Economics Centres (Centres d'Economie Rurale, CER) from Département de l'Aube and Département de la Haute Marne, and expert knowledge.

[13] From the REGIX project, financed by the French National Research Agency under the National Research Programme on Bioenergy.

[14] The French National Forest Survey, the French National Geographical Institute, and the Regional Wood and Forest Department.

[15] Distancier intercommunal Route 500, INRA UMR 1041 CESAER, Dijon.

[16] Wood transportation costs were provided by the FCBA, in the form of quadratic transportation cost functions. Crop transportation costs data were gathered and computed per distance interval by ARVALIS based on CNR 2008 data. The choice of the vehicle depends on the type of biomass, its conditioning, the slope of the forest stand, and the distance to cover. We account for 8 types of vehicle, 5 for wood and 3 for crops.

counties' gross margins, given 2006 agricultural prices in the region, subject to constraints on the sugar beet, starch potato, and food potato areas at *département* level. We compare our simulated land use to data on farms growing cereal, oilseed and protein crops, provided by the French agricultural bureau of statistics (Statistique Agricole Annuelle and Enquête structure 2007) at *département* level, which is the smallest administrative level for which data are available. Results show that they are quite similar. For more detail on validation results, see Bamière (2013).

2.3.3 Baseline

We run the model for the three initial price contexts with zero demand for lignocellulosic feedstock, which is currently the case, to obtain a baseline for agricultural production and wood harvest and use if there is no bioenergy facility operational in the region. Results are provided in Table 2.2 and Table 2.3. Table 2.2 shows that when agricultural prices are higher, the share of wheat, maize, and sunflowers tends to increase at the expense of barley, alfalfa, and rapeseed. Table 2.3 shows that the total amount of wood harvested remains quite similar regardless of the level of wood prices. However, when wood prices increase, the type of conditioning changes and logs are preferred to woodchips.

	Low		Benchmark		High	
	Area ($10\ km^2$)	Production (10^3 t)	Area ($10\ km^2$)	Production (10^3 t)	Area ($10\ km^2$)	Production (10^3 t)
Wheat	437	3,482	501	3,993	556	4,442
Spring barley	115	770	75	502	60	404
Winter barley	31	242	23	183	15	118
Rapeseed	109	396	95	347	83	300
Sunflower	34	102	61	169	113	327
Maize	93	710	108	879	121	1,002
Peas	39	156	36	174	0	0
Sugar beet	89	7,973	89	8,009	89	8,009
Potatoes	11	512	11	512	11	512
Starch Potatoes	5	206	5	206	4	186
Alfalfa	92	1,167	50	668	0	0

Table 2.2
Crop area and production for the baseline depending on the initial agricultural price level

Price level	Wood	Non-barked logs	Long barked logs	Short barked logs	Bundles	Woodchips	Total
Low	Softwood	548	0	396	61	1,352	2,358
	Poplar	104	33	0	4	0	141
	Hardwood	154	147	0	17	181	498
Benchmark	Softwood	548	0	1,111	61	645	2,366
	Poplar	104	33	0	4	0	141
	Hardwood	202	161	0	17	140	521
High	Softwood	548	0	1,676	61	81	2,366
	Poplar	104	33	0	4	0	141
	Hardwood	202	252	0	17	54	525

Table 2.3
Wood production for the baseline depending on the initial agricultural price level (10^3 metric tons)

2.3.4 Simulations

Price scenarios. The VAR model described above is used to simulate 500 anticipated price series (i.e., 500 price scenarios) over 15 years. Prices at $t = 0$ in the benchmark context are Champagne-Ardenne mean prices for the 1993–2007 period (and the 1st and 9th deciles for the low and high price contexts). Given that markets for vegetable oils are known to be strongly interrelated (In and Inder, 1997), we use price information on palm oil to substitute for the oilseeds represented in the model: rapeseed and sunflower. There is also a strong relationship between wheat and barley (Dawson et al., 2006). We assume that barley, peas and horse bean prices follow wheat price variations. The prices of the other crops (e.g., sugar beet, potatoes) are assumed to be constant over time. The different categories of wood are assumed to follow the price dynamics of timber estimated in the VAR model.

Contractual prices as well as the type and area of contracted perennial crops are fixed at $t = 0$, whereas model simulations to assess viability start at $t = 3$ when the facility is up and running and when perennial dedicated crops start to be productive.

Supplying strategies. We compare 6 supplying strategies, consisting in contracting either 0%, 20%, 40%, 60%, 80% or 100% of the lignocellulosic feedstock demand (in primary energy equivalent) with perennial crops, i.e., miscanthus, switchgrass or poplar SRC in our study. Remaining demand has to be satisfied each year with wood or annual dedicated crops, i.e., whole-plant triticale and fiber sorghum in our study. These strategies are denoted respectively sb0, sb20, sb40, sb60, sb80, and sb100.

2.4 Results

The results are presented as follows. We first describe the type, origin, and price of the biomass supplied in the various supplying strategies considered. Second, we compare strategies according to their viability probability, and show that strategies based on higher contractual shares are more viable. Last, we provide a sensitivity analysis of these results with respect to the price context of the contracting year, exhibiting the robustness of our analysis.

2.4.1 Agricultural land use and lignocellulosic biomass production

When a demand for lignocellulosic biomass appears, switchgrass silage is the perennial biomass contracted by and delivered to the bioenergy facility. The contracted perennial biomass (switchgrass) is grown in the county where the facility is located, on the region's most fertile and profitable soil categories (in terms of agricultural yields and gross margins). Its total area ranges from 6,716 ha to 33,582 ha depending on the supplying strategy (the larger the part of contracted biomass, the larger the area of switchgrass).[17] Its opportunity cost (i.e., P_0^{pc}) ranges from 12.95 €/MWh to 13.33 €/MWh (see Table 2.4), i.e., from 60.1 €/t to 61.9 €/t dry matter or from 1052.2 €/ha to 1083.1 €/ha.

The farm gate opportunity cost we obtain is consistent with what is currently offered to farmers for perennial crops in France. The fact that switchgrass is more profitable than miscanthus for farmers is also consistent with existing economic analysis at farm level in France (Bocquého and Jacquet, 2010).

	sb0	sb20	sb40	sb60	sb80	sb100
Shadow price of the contracted biomass, P_0^{pc}	–	12.98	12.95	13.33	13.28	13.07
Shadow price of the annual biomass for the base year, P_0^{ac}	19.74	19.44	19.27	18.99	18.58	–

Table 2.4
Supplied biomass prices for the different supplying strategies at $t = 0$ (€/MWh)

For supplying strategies that are not based exclusively on contracted perennial crops (i.e., sb0 to sb80), the residual, non-contracted demand is filled by annual dedicated crops. Table 2.5 shows the type and quantity (metric tons) of annual biomass supplied to the bioenergy facility on average over the 500 price scenarios. The larger the contractual

[17] At the region level, for the supplying strategy sb100, the demand for swithgrass leads to a decrease of alfalfa and peas areas by 14 to 12%, of wheat and maize areas by 4% and to a rise of spring barley areas by 6%.

biomass supply, the smaller the annual supply. Actual annual biomass supply in each scenario depends on the absolute and relative levels of agricultural prices. It is composed mainly of whole plant triticale and to a lesser extent of fiber sorghum and wood. It shows great variability over the price scenarios (standard deviation is often higher than the mean), which implies that the facility's transformation process has to be flexible. If the facility prefers to limit the supply to a few biomass sources, it will therefore be more expensive.[18]

	sb0		sb20		sb40	
	Mean	SD	Mean	SD	Mean	SD
Switchgrass	0	–	117,537	–	235,073	–
Whole-plant triticale	570,534	74,322	458,130	59,502	345,549	44,938
Fiber sorghum	61,533	60,901	48,249	49,418	34,955	37,568
Softwood logs	1,272	4,056	734	2,569	360	686
Softwood bundles	53	152	27	83	11	7
Softwood woodchips	31,642	53,076	24,599	43118	17,618	22,501
Hardwood woodchips	416	1,005	247	616	130	151
	sb60		sb80		sb100	
Switchgrass	352,610	–	470,146	–	587,683	–
Whole-plant triticale	231,177	30,391	112,847	16,894	–	–
Fiber sorghum	22,988	25,329	14,502	14,796	–	–
Softwood logs	133	686	25	153	–	–
Softwood bundles	3	7	1	2	–	–
Softwood woodchips	11,133	22,501	5,214	11,170	–	–
Hardwood woodchips	64	151	27	57	–	–

Table 2.5
Type of biomass delivered to the facility in the benchmark case (mean and standard deviation over the 500 price scenarios, metric tons)

For example, at the initial time, demand is satisfied by whole-plant triticale. This annual dedicated crop substitutes to spring barley and wheat in the rotations usually grown in the three most fertile and profitable soil categories in the region.[19]

Depending on the supplying strategy, the opportunity cost of whole-plant triticale silage ranges from 18.58 €/MWh (for sb80, where only 20% of biomass demand is filled by annual crops) to 19.74 €/MWh (for sb0, where total demand is filled by annual crops). This gives the opportunity cost of the last unit of energy delivered to the facility (i.e.,

[18] Our model can easily be modified to account for constraints on the type and quality of biomass delivered to the facility.

[19] At the region level, for sb0 at $t = 0$, it leads to a decrease of spring barley and peas areas by circa 30%, of wheat and maize areas by circa 5% and to a rise of alfalfa and winter barley by respectively 26 and 19%.

P_0^{ac}).

Note that in this benchmark case, the shadow price of the contracted biomass is always lower than the price of annual biomass at the initial time (see Table 2.4). This means that it is less costly to supply the bioenergy facility with perennial dedicated biomass (i.e., switchgrass) than to use annual energy crops or wood.

Fig. 2.2 depicts the geographical origin of biomass for three supplying strategies: "0% contractualization" strategy (sb0), "60% contractualization" (sb60), and "100% contractualization" (sb100). When there is no contractual biomass supply, many counties supply small quantities of annual dedicated crops, except for four that each supply between 10% and 17% of the demand. When the contractual part increases, i.e., when demand for perennial biomass increases, the supply from each county (except for the county where the facility is located) decreases and the number of supplying counties actually decreases. The county of the biofuel facility provides the perennial dedicated crops. In the extreme case of total contractual supply, this same county produces only dedicated perennial crops (i.e., switchgrass), satisfying the totality of the plant's demand. From a logistic point of view, the fact that perennial crops are located in a single county, which is the same as that of the facility, should reduce transaction costs.

2.4.2 Viability of the strategies

We next turn to analysis of the viability of the various supplying strategies. Fig. 2.3(a) exhibits the viability probability of a range of strategies as a function of the profitability threshold price.[20] The horizontal axis corresponds to a continuum of possible values for the constraint threshold $\bar{P}$ characterizing the economic viability constraint (equation (2.2)). The vertical axis provides the viability probability that allows us to rank supplying strategies. The six curves correspond to the performance of six supplying strategies that vary in their share of contracted biomass, respectively with 0, 20, 40, 60, 80 and 100% of input biomass from perennial crops. Each curve gives the viability probability of the corresponding supplying strategy with respect to the level of the profitability threshold. For any threshold level, the higher the share of contracted biomass, the higher the associated viability probability. Our results are valid whatever the profitability threshold and, thus, are robust to uncertainties for this parameter value.

For every strategy, the lower the profitability threshold, the lower the viability probability. Stronger economic constraints are harder to meet. In that respect, the strategy of

[20] In all the subfigures, the interpretation is the same. We start by describing the benchmark case. The "low contractual price" and "high contractual price" cases are discussed in the next subsection.

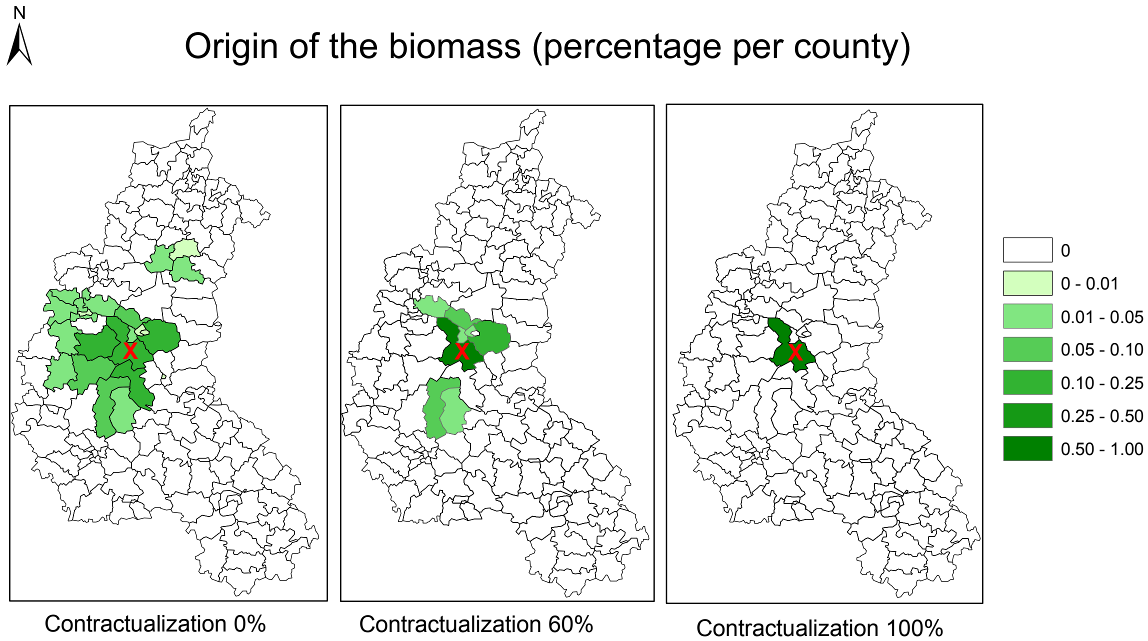
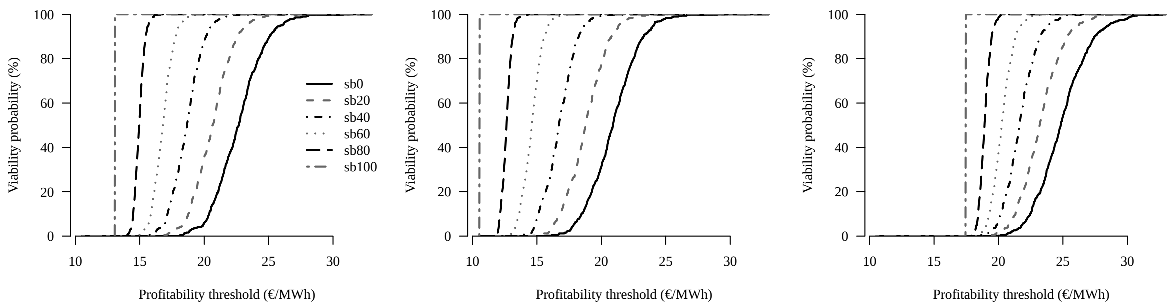


Fig. 2.2. Biomass supply per county (percentage of total supply) at $t = 0$



(a) Benchmark case **(b)** Low contractual price **(c)** High contractual price

Fig. 2.3. Viability probability as a function of the profitability threshold for a range of strategies

total contractual supply sb100 exhibits an extreme behavior, with a nil viability probability for any profitability threshold lower than the contractual price, and a 100% viability probability for any profitability threshold larger than the contractual price. For other strategies, the viability probability varies smoothly with the profitability threshold. For each strategy, the viability probability reaches 100% for some profitability threshold. This provides economic conditions for the robustness of the strategy, i.e., if the actual profitability threshold is higher than that level, the strategy will succeed in all scenarios.

Taken together, our results mean the following. For a bioenergy facility characterized by a given profitability threshold, contracting a larger share of the biomass supply results in higher viability probability. Setting contracts to ensure supply at a given cost is thus a good strategy to achieve the economic and technological viability of a bioenergy facility in an uncertain economic context.

Average total and per energy unit supply costs range respectively from 428 to 651 million euros and from 13.07 €/MWh to 19.88 €/MWh (see Table 2.6). The strategy consisting in contracting the whole demand is the cheapest.

	sb0		sb20		sb40		sb60		sb80		sb100	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Low price context												
Total supply cost	600	43	547	35	495	267	443	17	397	8	345	0
MWh supply cost	18.33	1.30	16.71	1.06	15.12	0.81	13.54	0.53	12.13	0.25	10.55	0
Benchmark case												
Total supply cost	651	47	601	39	553	30	513	19	471	9	428	0
MWh supply cost	19.88	1.44	18.37	1.18	16.89	0.91	15.66	0.59	14.40	0.28	13.07	0
High price context												
Total supply cost	709	51	675	42	644	32	621	21	598	10	571	0
MWh supply cost	21.64	1.57	20.61	1.28	19.66	0.99	18.97	0.64	18.26	0.32	17.45	0

Notes: Mean and standard deviation over the 500 price scenarios.

Table 2.6
Total (in million € for the 13 years horizon) and per energy unit (€/MWh) supply costs for each strategy and initial price context.

To better understand these results, we examine their sensitivity to the contractual price, which, in our model, is related to the economic context (in terms of agricultural commodity prices and opportunity cost to produce perennial crops).

2.4.3 Effect of the initial economic context

We perform a sensitivity analysis of our results to the initial contractual price by computing the opportunity cost of perennial crop supply in different economic contexts. We consider first a "low price" context and then a "high price" context. The prices prevailing when the contracts are signed matter because commodity prices are serially correlated, so periods of low (high) prices tend to be followed by periods of low (high) prices. Even if, in the long-run, prices return to their steady-state distribution, farmers account rationally for the transitional dynamics of prices and accept lower (higher) contractual prices when prices are low (high). Our results are robust to the agricultural commodity price context.

Lower contractual price case. We perform the same simulation as in the previous analysis, but starting from a vector of lower agricultural and wood prices (Fig. 2.3(b)). Comparison of the contractual prices (opportunity cost of perennial energy crops) is provided in Table 2.7. When the contractual price is low, e.g. if it is set in an economic context characterized by low agricultural commodities prices and thus a low opportunity cost to contract, the viability probability of all the considered strategies increases.

Initial price level	sb20	sb40	sb60	sb80	sb100
Low contractural price	10.91	10.92	10.83	10.82	10.55
Benchmark case	12.98	12.95	13.33	13.28	13.07
High contractual price	16.94	17.07	17.64	17.66	17.45

Table 2.7
Contractual price of perennial energy crop (€/MWh) - Sensitivity to the initial economic context.

An initial context characterized by lower agricultural prices results in lower contractual prices, but also in lower opportunity costs for annual dedicated crops. The viability probability of all strategies improves. Also, lower profitability threshold constraints are met with higher probability. The ranking of strategies, however, is not affected. The strategy that consists in contracting all the biomass supply still meets the viability constraint with a higher probability than for the other strategies.

In terms of type of biomass supplied, silage switchgrass is still the perennial crop contracted by the facility, at a cost ranging from 10.55 €/MWh to 10.92 €/MWh, and produced in the same county on the same soil type.[21] The average annual biomass supply (over the 500 price scenarios) is still composed of whole plant triticale silage, fiber sorghum silage and wood (mainly softwood chips). However, the share of sorghum increases at the expense of triticale.[22]

The average total and per energy unit biomass supply costs are lower than in the benchmark case for all strategies (see Table 2.6).

Higher contractual price case. We performed the same simulations as in the benchmark case, but starting from a vector of higher agricultural prices corresponding to the

[21]For sb100, switchgrass production leads to a decrease of alfalfa and spring barley areas by 11% and of wheat, winter barley, rapeseed and maize by 2 to 4%.

[22]When fiber sorghum silage is delivered to the facility, it is mainly grown on a less fertile soil category. At the region level, for sb0 at $t = 0$, the substitution of fiber sorghum and whole plant triticale to respectively maize and spring barley leads to a decrease by 30% of maize area and by 21% of spring barley area.

9^{th} decile of 1993–2007 prices (Fig. 2.3(c) and Table 2.7). The conclusions still hold when the contractual price is high, though the profitability threshold of all strategies increases.

In terms of type of biomass supplied, silage switchgrass is still the perennial crop contracted by the facility, at a cost ranging from 16.94 €/MWh to 17.66 €/MWh, and produced in the same county on the same soil type.[23] The average annual biomass supply (over the 500 price scenarios) is still composed of whole plant triticale silage, fiber sorghum silage and wood (mainly softwood chips). However, the share of triticale and wood increases at the expense of fiber sorghum. In addition, the standard deviation of wood and sorghum supply over the 500 price scenarios increases. Whole plant triticale is still the non-contractual dedicated crop delivered to the facility at $t = 0$ in the supplying strategies sb0 to sb80, and it is grown on the two most fertile soil categories of the region.[24]

The average total and per energy unit biomass supply costs are higher than in the benchmark case for all strategies (see Table 2.6).

2.5 Discussion and conclusion

Meeting the increasing targets of bioenergy production without harming the environment requires development of viable second generation bioenergy chains. Their viability depends on both the local availability of biomass and the profitability of production. These elements are strongly influenced by the economic context and uncertain agricultural commodity prices, and the resulting opportunity cost of producing energy crops.

In the present paper, we use a stochastic viability approach to examine the economic and technological viability of a second generation bioenergy facility. We consider a technological constraint on biomass supply, and an economic constraint on supply cost. The profitability threshold characterizing this latter constraint is treated as a parameter in the sensitivity analysis. We examine the viability probability of various supplying strategies, i.e., the probability with which these strategies respect the constraints over time. We show that the strategy of contracting total biomass supply with perennial dedicated energy crops maximizes the viability probability.

From a decision making point of view, our results suggest that the viability of sec-

[23]For sb100, switchgrass production leads to a decrease in maize, sunflower, and wheat areas by 6 to 4% and to an increase in spring barley areas by 6%. It is noteworthy that for this price context, neither alfalfa nor peas are grown.

[24]At the region level, for sb0 at $t = 0$, the substitution of whole plant triticale to respectively spring barley and wheat leads to a decrease of spring barley areas by 42%, of wheat, maize, and sunflower areas by 2 to 3%, and a slight increase of rapeseed by 4%.

ond generation bioenergy facilities strongly depends on the availability and cost of local biomass supply, which, in turn, is strongly affected by other commodity price uncertainties. Setting contracts that ensure both supply of the required quantity and its cost is an efficient strategy to limit the risk of non-viability related to the uncertain agricultural commodity prices, at least when such contracts can be set at a sufficiently low price with respect to the profitability threshold.

An interesting result of our modeling exercise is that both the contracted perennial biomass and the non-contracted annual dedicated biomass are produced mainly on the best quality land across the region. Second generation biofuel facilities may induce competition with conventional crops for the most productive land .

In this study we assume that the contractual price will equal the opportunity cost of the last energy unit delivered to the facility. However, this is probably underestimated for two reasons. First, in our simulations, dedicated biomass is sometimes grown on 100% of the crop growing farms area, whereas farmers are generally reluctant to introduce mass production of new crops. Second, farmers will probably ask for a price revision over time since it is a long-run contract. We also do not consider farmers' liquidity constraints or risk aversion. Bocquého and Jacquet (2010) suggest that the combination of a guaranteed fixed price and a subsidized loan to finance perennial crops establishment cost enhances the adoption of such crops by farmers.

Last, as the size of facilities influences their optimal location and profitability (Kocoloski et al., 2011), future research could examine how the size of the bioenergy facilities modifies their viability in a given region.

Deuxième partie

Conservation de la biodiversité en milieu agricole

La deuxième partie de cette thèse correspond à des travaux menés dans le cadre de deux projets de recherche interdisciplinaires, financés par l'Agence Nationale de la Recherche :

- le projet PRAITERRE « PRAIries TERritoires Ressources et Environnement : la place et le rôle des prairies dans la gestion agri-environnementale et écologique d'un territoire de polyculture-élevage » (ANR-05-PADD-002, 2005-2008), dans le cadre du programme Agriculture et Développement Durable. Ce projet était coordonné par Gille Lemaire (INRA).

- le projet BiodivAgriM « Conservation de la biodiversité dans les agro-écosystèmes : une modélisation spatialement explicite des paysages » (ANR-07-BDIV-002, 2008-2011), coordonné par Vincent Bretagnolle (CNRS) et faisant suite au projet PRAITERRE.

Le projet PRAITERRE avait pour cadre une zone Natura 2000 de Poitou-Charente située dans la Plaine de Niort. Il s'agit d'un territoire traditionnellement de polyculture-élevage, qui subit depuis quelques années une forte spécialisation en grandes cultures et une diminution des surfaces en herbe, qui est confronté à des conflits autour de la gestion de l'eau et à des enjeux majeurs en termes de biodiversité. Cette région abrite des espèces patrimoniales menacées, dont l'Outarde Canepetière. L'objectif général du projet était de concevoir, évaluer et mettre en œuvre des formes nouvelles d'association entre activités de production céréalière et activités d'élevage d'herbivores, qui puissent engendrer une forme de développement rural plus durable que les tendances actuelles.

Les chapitres 3 et 4 correspondent à deux articles publiés, issus respectivement des projets PRAITERRE et BiodivAgriM :

- Bamière, L., Havlik, P., Jacquet, F., Lherm, M., Millet, G. and Bretagnolle, V. (2011). Farming system modelling for agri-environmental policy design : The case of a spatially non-aggregated allocation of conservation measures. Ecological Economics, 70(5), 891–899.

- Bamière, L., David, M., Vermont, B. Agri-environmental policies for biodiversity when the spatial pattern of the reserve matters. (2013). Ecological Economics, 85, 97–104.

Chapter 3

Farming system modelling for agri-environmental policy design: The case of a spatially non-aggregated allocation of conservation measures

Abstract

This paper addresses the issue of designing policies for habitat conservation on agricultural land. The case under study requires a non-aggregated spatial distribution of the fields to be enrolled in an agri-environmental programme. A spatially explicit mathematical programming farm-based model, which accounts for three spatial levels (field, farm and landscape), is coupled with a relevant spatial pattern index (the Ripley L-function) to analyse the design and implementation of an agri-environmental programme aimed to preserve the Tetrax tetrax in the Plaine de Niort, France. The model is run using a stylised map with heterogeneous soil types and both crop growing and mixed dairy farms. Results show that valuable insights into agri-environmental programme design are gained through a detailed representation of farming system management. The suitable, non-aggregated spatial pattern for Tetrax tetrax conservation is more costly than less-suitable, more aggregated patterns, because it tends to require equal participation of all farms. The policy simulations reveal that the various spatial patterns can be obtained through relatively simple uniform contract structures. An effective contract structure entails a set of two degressive payments which encourages all farms to enrol

at least a small share of their land in the program.

3.1 Introduction

Over the last fifty years, in western European countries, dramatic changes have taken place in the farming landscape. This is mainly due to mechanisation, the intensification of farming techniques and farm specialization as well as increases in the use of chemicals and the size of agricultural fields. While the productivity of European agriculture has considerably increased over this period, the range of biodiversity has suffered (Pain and Dixon, 1997, ?, Chamberlain et al., 2000, Donald et al., 2001). For example, common farmland birds of Europe have declined by 25% over the last two decades (Gregory et al., 2005). In the early 1990s, in order to minimize the negative environmental impacts of agriculture intensification, agri-environmental policies were integrated into the Common Agricultural Policy. The Natura 2000 programme was initiated to protect the most seriously threatened habitats, including those in farmland areas. In the latter case, specific agri-environmental regulations and incentives have been implemented by Member States to promote farming practices that ensure biodiversity.

This is the case in the Plaine de Niort (Poitou-Charente), France, where a Natura 2000 site has been designated to halt the decline of Tetrax tetrax (Little Bustard), an Annex 1 species of the EU Birds Directive (79/409/EEC). The Poitou-Charente region, located in western France, harbours the sole remaining Little Bustard migratory population in farmland areas. This population has undergone one of the steepest declines ever documented for a contemporary bird species in Europe, i.e., from a high of 7,800 males in 1978 to a low of 300 in 2008, attributed to land use changes and the intensification of agriculture [1]. Over the next 30 years, the Little Bustard has a 45% chance of undergoing extinction (Inchausti and Bretagnolle, 2005). These birds mate and breed in an arable landscape that is composed of alfalfa, grasslands, and annual crop fields (Salamolard and Moreau, 1999; Wolff et al., 2002). Their conservation in the Natura 2000 site requires a non-aggregated distribution of extensively managed grasslands.

In this paper, we address the issue of designing a Little Bustard-friendly (LBF) agri-environmental programme (AEP). This type of programme not only implies devising the incentives needed to encourage farmers to adopt LBF conservation measures. It must also take into account the important role of the spatial allocation of the fields to be enrolled in any undertaken conservation programme. Our investigation into this is innovative

[1]The estimated French population size was 8,500 males in 1978-1979, falling to 1,300 males in 2000 (Jolivet and Bretagnolle, 2002).

in two ways. Firstly, we present a spatially explicit mathematical programming model which consistently links several detailed farm-level models with the field and landscape levels. It is thereby able to endogenously assess the location and cost of fields to be enrolled in the programme. Secondly, this model is associated with a relevant spatial pattern indicator (the Ripley L function) to address the as yet untreated issue of a non-aggregated distribution of fields enrolled for conservation and to discuss the design of an AEP aimed at providing such a spatial pattern.

The presented approach is related to the vast literature investigating, on the one hand, reserve site selection and reserve design, and, on the other hand, agri-environmental and conservation policy design. Reserve site selection has been largely studied in the field of conservation biology (e.g., Kirkpatrick, 1983; Vanewright et al., 1991). It generally involves minimizing the number of sites or total reserve area necessary to protect a given set of species. Or, inversely, studies aim to maximize the number of species protected for a given number of sites or total reserve area. More recently, economists have introduced land costs and budgetary issues into the analysis to address the issue of cost-effectiveness (i.e., to minimize costs for a given conservation effort, Ando et al., 1998; Polasky et al., 2001; Naidoo et al., 2006). In contrast to reserve site selection, reserve design models account for the spatial aspects of the reserve, comprehensively reviewed by Williams et al. (2005). Studies devoted to both approaches define "reserve" as undisturbed nature. However, a conservation strategy based on nature reserves or national parks is neither appropriate nor achievable in most of the farmed European landscapes. Hence, "working land" as well as alternative land uses and management options must be integrated into the analysis (e.g., Polasky et al., 2005, 2008; Nalle et al., 2004). This has been done for agricultural land by authors like Wossink et al. (1999) or van Wenum et al. (2004). While the above-mentioned studies focused more on the question of where the "reserve" should be set up, another important issue is how to implement these desirable "reserve" spatial patterns. Optimal reserve design studies usually assume that the social planner has perfect knowledge of all costs and selects sites based on their opportunity cost, which he compensates for. In reality, conservation policies are often incentive-based because governmental agencies enforcing them only have imperfect information on private costs, or, even if the Government sometimes has the necessary information, it cannot use it for political reasons (Chambers, 1992). Recent work has been carried out on a regional basis which has explicitly taken into account spatial landscape patterns in the effects of incentives-based policies for conservation on agricultural land (e.g., Drechsler et al., 2007, 2010; Hartig and Drechsler, 2009; Johst et al., 2002; Lewis and Plantinga, 2007; Lewis et al., 2009; Wätzold and Drechsler, 2005; Wätzold et al., 2008). However, these studies either do not account for the farm level, or they oversimplify farmers' behaviour, while they all consider exogenous land-use opportunity costs for individual plots. The latter assumption overlooks the fact that in a farming system the opportunity cost of a change in land use or land management on one field does not exist independently of other decisions due to, for instance, rotational effects or cattle feeding requirements. As pointed out by Hynes et al. (2008), it is the farmers who ultimately take the decision and therefore determine the effectiveness and efficiency of an agri-environmental programme. Based on the representation of the technical and economic behaviour of farms, mathematical programming farm-level models have largely been used by agricultural economists to assess the efficiency of environmental policies (e.g. Falconer and Hodge, 2001; van Wenum et al., 2004; Ekman, 2005, or Havlik et al., 2005; Wossink et al., 1992). However, this modelling framework has rarely been used to address the issue of the spatial location of production choices. Our approach departs from the existing literature in that we have developed a spatially explicit and detailed farm-based optimization model in which technical and administrative constraints influencing land management choices, in addition to farmers' profit-maximizing behaviour, are accounted for at the farm level. This model is thus able to determine endogenously farmers' conservation compliance costs, and it can be used both for the analysis of the spatial allocation of conservation measures and for AEP design. Our approach is also different from the existing literature because we account for a non-aggregated spatial distribution of fields to be enrolled in a conservation effort. As Williams et al. (2005) have pointed out, the spatial configuration of reserves matters if we are to ensure the long-term persistence of species. The choice of the reserve spatial attribute to retain, such as connectivity or shape, depends on the species and conservation objectives. While contiguity and connectivity have often been studied (e.g., Wossink et al., 1999; Nalle et al., 2004; Parkhurst and Shogren, 2008), to the best of our knowledge, in the field of spatially explicit modelling of biodiversity conservation in agricultural land, this study is the first attempt to account for a non-aggregated spatial distribution of land

The paper is structured as follows. The methodological aspects involving the modelling approach, the conservation problem, and the method used to characterize the mosaic landscape are covered in Section 3.2. The area under study and the applied model are described in Section 3.3. In Section 3.4, we explore where the extensively managed grasslands should be located so that the cost, in terms of foregone farm income, is the lowest, accounting for soil heterogeneity. We also investigate the trade-off between a deviation from the desired non-aggregated pattern and the corresponding cost change. We then examine different payment schemes likely to produce these landscape patterns and evaluate them in terms of landscape pattern quality and budgetary expenditure. In Section 3.5, we conclude, discuss the adopted approach and our findings, and make suggestions for further developments.

3.2 Methodology

3.2.1 Modelling approach

OUTOPIE (OUTil pour l'Optimisation des PrairIes dans l'Espace) is a mixed integer linear programming model which accounts for three spatial levels: field, farm and landscape/region. The field represents the elementary unit of the model. Field characteristics, such as soil, climate and slope, determine the potential agricultural activities and cropping techniques that can be chosen by the farmer as well as the resulting yield and gross margin. In our model, fields are characterised by their soil type, irrigation equipment (or not), and the farm to which they belong. The farm is the level at which decisions concerning land allocation are made, taking into account regulation and policy constraints (e.g., milk quotas and obligatory set aside), as well as technical constraints such as feed requirements. Finally, spatial relationships between fields relevant for the Little Bustard are accounted for at the regional level. From this section on, we will refer to alfalfa and temporary or permanent grassland, enrolled in a Little Bustard Friendly (LBF) agri-environmental programme, indifferently as LBF managed grasslands, land for Little Bustard conservation, or land enrolled in the Little Bustard conservation programme.

The model, in general, maximizes the sum of all farms' gross margins-including payments and costs due to the participation in an LBF agri-environmental programme-subject to field, farm and landscape level constraints.

This is represented in optimisation programme (3.1), where $X_{f,i,c}$ is the level of the different farm activities for farm f, on field/plot i enrolled (or not) in one of the LBF managed grassland types c. Π_f is the farm gross margin from agricultural activities; cp_c is the compensation payment for a LBF managed grassland type c; vtc_c is a variable transaction cost per hectare of enrolled land; ftc is a fixed private transaction cost per farm and P_f is a binary variable equal to 1 if the farm participates in the agri-environmental program (AEP); and ptc is a fixed public transaction cost per farm participating in the AEP. We considered both private and public transaction costs as they play an important role in both the cost of agri-environmental policies and the farmers' decision to take up the agri-environmental programme (Falconer et al., 2001).

$$\max \sum_f [\Pi_f(X_{f,i,c}) + \sum_{c,i}(cp_c - vtc_c)X_{f,i,c} - ftc \cdot P_f] - ptc \cdot \sum_f P_f \quad (3.1)$$
$$s.t. \quad Field(X_{f,i,c}), Farm(X_{f,i,c}), Landscape(X_{f,i,c})$$

The model can be used either to investigate where the LBF managed grassland fields should be located or to test agri-environmental policies. In the first case, a constraint is introduced that imposes-at the landscape l evel-the minimum area CA to be enrolled in the Little Bustard conservation programme and its required spatial distribution corresponding to a value of a spatial indicator SI (see equations (3.2) and (3.3)). Compensation payments are set to zero and the public transaction cost ptc per farm is positive. The cost of the land required to ensure LB conservation is calculated as the difference between the sum of gross margins (including private transaction costs) without and with constraints (3.2) and (3.3), plus the public transaction cost.

$$\sum_{f,i,c} X_{f,i,c} \geq CA \quad (3.2)$$

$$SI(X_{f,i,c}) \geq SI \quad (3.3)$$

In the second case, agri-environmental payments that compensate farmers for the fields enrolled in the LBF AEP are strictly positive, and their impact on the size and location of the contracted fields is evaluated through equations (3.4) and (3.5). The latter two are simply constraints (3.2) and (3.3) transformed into accounting equations by replacing the exogenous conservation requirements, CA and SI, by equivalent accounting variables ConservedArea and SpatialIndicator. The public transaction cost ptc is set to zero in the objective function as it does not affect farmers' decision to take up the AEP. Instead, it is used to compute the total cost of the conservation programme post-optimisation, which-in addition to the cost of land under conservation mentioned above-also accounts for the informational rent received by farmers that depends on the way the compensation payment is awarded[2].

[2] E.g. uniform payment per hectare needs to compensate for even the most expensive last plot enrolled in the AEP; there is therefore a rent, arising on all the cheaper fields, which is equal to the difference between the compensation payment and the actual conservation cost (the conservation cost is equal to the profit foregone plus the private transaction costs).

$$\sum_{f,i,c} X_{f,i,c} = ConservedArea \tag{3.4}$$

$$SI(X_{f,i,c}) = SpatialIndicator \tag{3.5}$$

Individual cropping and breeding activities, agri-environmental measures, transaction costs, and data sources used in the model are further detailed in Section 3.3.

3.2.2 Spatial pattern analysis

The decline in Little Bustard populations has been attributed to the decrease in extensive grasslands in farmland habitat (Bretagnolle, 2004). In fact, this decrease affects the insect abundance on which the bird depends. Adult Little Bustards mainly feed on insects during the summer and bustard chicks feed exclusively on grasshoppers (Jiguet, 2002). In order to maximise grasshopper distribution and abundance in agricultural habitat, extensive temporary grasslands should be distributed throughout the landscape in rather small patches, especially if the total area of grassland is limited, such that the dynamics of the metapopulation ensures the persistence of insect populations (Hanski, 1999; Appelt and Poethke, 1997). In addition, Little Bustards show a lekking mating system with an extreme separation of sexes in their role to achieve breeding (males are only involved in copulation for breeding, Jiguet et al., 2000). For mating to occur, females must be readily able to detect males who therefore display themselves on low cover, for instance sunflower, which, in spring, is in an early stage of growth, or ploughed land. Females, however, prefer alfalfa, grasslands and fallow, where they find both shelter and food (Salamolard and Moreau, 1999; Jiguet, 2002; Wolff et al., 2001, 2002). The most suitable landscape spatial pattern for Little Bustard conservation therefore requires the following two characteristics: at least 15% of the land should be covered by extensively managed grassland patches (3 ha being the ideal field size); and the patches should be located in function of a non-aggregated pattern. In the given case, within any radius between 100 and 1000m, the fields should be randomly distributed, as opposed for example to an aggregated or an over-dispersed pattern (Bretagnolle, 2004; Bretagnolle et al., 2011, see Figure 3.1(a) for an example of random vs. aggregated distribution).

Given these two characteristics, we need to measure not only the total area of fields enrolled in the conservation programme but also their spatial pattern. The former being straightforward, we will focus here on the measurement of the spatial pattern with the Ripley K and L functions.

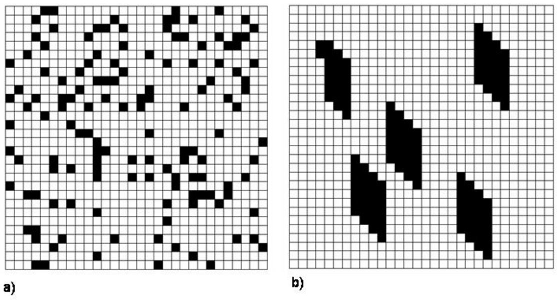


Fig. 3.1. Examples of the spatial distribution of 135 conservation plots on a 900-plot grid: a) random, b) aggregated.

The Ripley K and L functions (Ripley, 1977, 1981) are part of spatial point pattern analysis methods. These functions combine density counts and distances, and account for spatial structures at different scales. They are widely used in plant ecology and can be used to study stationary constructions (Haase, 1995).

The Ripley K and L functions are the most appropriate indices for the present study. Let A be the area of the zone under study, N the number of observed LBF-managed grassland plots, and λ the density ($\lambda = N/A$). $\lambda \bullet K(r)$ can be interpreted as the expected number of further LBF managed grassland plots within a radius r of any arbitrary plot. If the fields dedicated to conservation are randomly located, following a Poisson distribution, then the expected value of $K(r)$ equals πr^2. $\hat{K}(r)$ is an unbiased estimator of $K(r)$ calculated as follows:

$$\hat{K}(r) = \frac{1}{\lambda N} \sum_{i} \sum_{j \neq i} \left(w_{i,r} \cdot I_r(d_{i,j}) \right) \tag{3.6}$$

where $d_{i,j}$ is the distance between two LBF managed grassland plots, I_r a binary variable equal to 1 if $d_{i,j} \leq r$ or to 0 otherwise, and $w_{i,r}$ an edge-effect-correction weighting factor. Like many others, we apply the normalised form of $\hat{K}(r)$, i.e., $\hat{L}(r)$ (Besag, 1977; Ripley, 1981), which has an expected value of zero for a random Poisson distribution (see equation 3.7).

$$\hat{L}(r) = \sqrt{\frac{\hat{K}(r)}{\pi}} - r \tag{3.7}$$

Once the $\hat{L}$ function is assessed for the spatial distribution of the plots under conservation in a scenario, it has to be tested against the null hypothesis of Complete Spatial

Randomness (Diggle, 1983). We used the Monte Carlo method to create a 95% confidence envelope[3]. Results can be interpreted as follows (c.f. Fig. 3.1 for two spatial distributions of the fields under conservation and Fig. 3.2 for the associated values of $\hat{L}$): a) if $\hat{L}(r)$ remains within the confidence envelope (dotted lines in Fig. 3.2) then the spatial pattern of the LBF managed grassland fields is significantly (Poisson) random; b) if the deviation from zero is significantly positive, i.e., $\hat{L}(r)$ is above the upper limit of the confidence envelope, then the spatial pattern is clustered or aggregated. The scale of interest and the intervals between radii depend on the species and the issue which is being addressed. In our case, the analysis of the Ripley $\hat{L}(r)$ function should be limited to the Little Bustard relevant radii ranging from 100 to 1 000 metres, and to intervals equal to the distance between two fields.

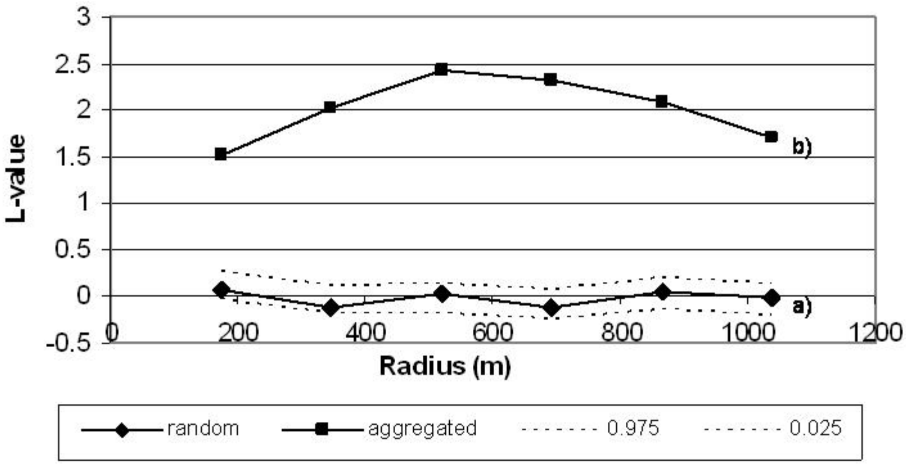


Fig. 3.2. Ripley L function for the random (a) and aggregated (b) distributions

3.3 Case Study

3.3.1 Stylising the area under study

Our research is focused on a core area of the Poitou-Charente region: a Natura 2000 Special Protection Area located in the Plaine de Niort (FR5412007), the French département des Deux-Sèvres. This area was traditionally dedicated to mixed farming but has

[3] More details on the computation and interpretation of the Ripley K and L function are provided in appendix 1.

undergone a rapid specialisation in crop production: more specifically, the area in meadows and pastures dropped by 60% between 1988 and 2000 to currently represent only 13% of the local agricultural area. It is being replaced by annual crops (mainly wheat, maize, and rapeseed). Between 1988 and 2000, the number of mixed farms dropped by 40% to currently represent only 26% of the agricultural area of les Deux-Sèvres. The entire Natura 2000 site includes about 20,000 ha and is composed of circa 7000 fields.

We have chosen to concentrate on a stylised area restricted to 2,700 hectares divided into 900 fields, 3 hectares each (cf. Fig. 3.3). The size and characteristics of this stylized area are consistent with local ecological and economic considerations :i) a sustainable Little Bustard population of about 20-25 individuals (i.e., 3-4 leks; Inchausti and Bretagnolle, 2005) lives on approximately 3-5 000 hectares, ii) a 3-hectare grassland patch size is required for Bustard conservation, and it is close to the current average field size within this Natura 2000 site; iii) different soil qualities are represented according to the observed ratio and layout ; iv) the two main farming systems (crop and mixed-dairy farms) are accounted for. We decided not to account for differences in farm size or farm plot distribution. We therefore took all farms to be 150 ha in size, with aggregated fields, allowing us to better assess the impact of soil heterogeneity between farms on their participation in the AEP and on the location of enrolled fields.

3.3.2 Modelling crop and mixed dairy farms

On a crop farm, the basic decision variable is the share of each field allocated to a specific crop rotation. The model accounts for the major crops (wheat, winter barley, sunflower, rapeseed, maize, and sorghum), for permanent as well as temporary grasslands, including alfalfa, and for set aside land. Crops are divided into different cropping activities depending on i) the preceding crop, ii) crop use, iii) the duration of perennial crops (e.g., alfalfa cultivated for 3 or 4 years) and iv) the cropping technique (rain-fed, irrigated or LBF). These crops are combined into 52 crop rotations including new rotations devised to let farmers adapt their production system to the agri-environmental programme. Crop rotations and yields on each of the soil types were provided by agronomists and local experts[4].

Mixed dairy farms optimize crop rotations as well as the herd size and composition,

[4] The information has been collected inside an interdisciplinary research project, coordinated by G.Lemaire, INRA-Lusignan. Information on alfalfa and grassland management was provided by M.Laurent UEFE, INRA-Lusignan. For the other crops, yields were evaluated for each type of soil, taking into account the preceding crop effect, using the PERSYST model developed by L. Guichard, UMR Agronomie INRA-Grignon.

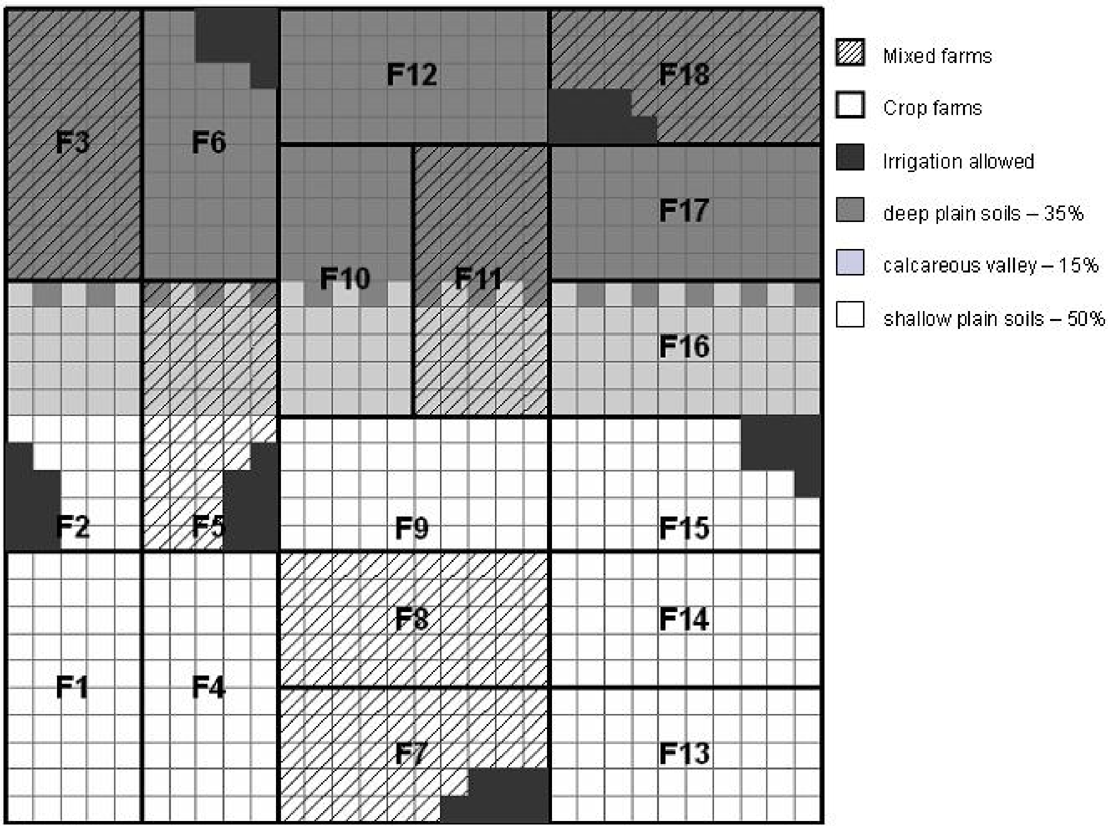


Fig. 3.3. Model representation of the area under study.

the choice of feed rations, the purchase of concentrates, and the purchase or sale of forage crops. They are subject to constraints such as milk quotas and cattle demography. The link between the herd size and milk production is achieved through feed rations. The dairy-cattle breeding module [5] accounts for 18 animal types (differentiated by age, state and feed requirements), 7 forage types (grazed grass, grass hay, grass silage, alfalfa hay, maize silage, cereals, and cattle-cake) and 80 feed rations. The policy framework of our investigation is based on the 2003 CAP reform, with a 10% obligatory set aside rate. Single payments and decoupled premium for animals were calculated with local references. Crop prices and production costs are based on data from the 2005 FADN, the regional Centre d'Economie Rurale and experts. Production costs and prices for milk and animals were provided by Institut de l'Elevage, Poitou-Charente, for 2005. For cash crop farms, the production of alfalfa is a new cropping activity, encouraged by the agri-environmental payments and for which farmers could possibly have an outlet by selling it to the local dehydration firm involved in fodder production. In order to avoid the overestimation of compensation payments, we have therefore included the possibility for all farms in the model (crop growing and mixed-dairy farms) to sell alfalfa at the market price (see Table 3.1).

3.3.3 Modelling the LBF agri-environmental schemes

In the studied area, an agri-environmental programme is currently implemented to encourage farmers to maintain and expand grasslands and to manage them in a Little Bustard-friendly way. This LBF management is characterized by restrictions on livestock density, fertilisation, pesticides, and mowing dates. In the model we consider as land under conservation all the land use types eligible for the Little Bustard AEP, i.e., permanent grasslands, temporary grasslands and alfalfa fields. The current LBF AEP requirements and compensation payments are detailed in Table 3.1.

The aim to analyse precisely the spatial pattern of the fields enrolled in the conservation programme requires two adjustments of the model structure presented so far. First, the decision variables which express the share of each plot enrolled in the conservation programme are to be binary. Second, in order to observe the location over time of fields to conserve, we add an index to each LBF conservation relevant crop rotation, indicating at which stage the rotation starts. To keep things simple, we did not introduce a discount

[5] The dairy cattle breeding module is derived from the Opt'INRA model, initially developed for suckler cow breeding (Veysset et al., 2005) and adapted to dairy cows in Poitou-Charente by LEE INRA Clermont-Theix. Feed rations are based on local practices or composed with the use of INRATion software (Agabriel et al., 1999).

Current AEP payments for LBF management	Permanent grassland 91.5 €/ha, Temporary grassland 110 €/ha, Alfalfa 450 €/ha
LBF management requirement	
– Permanent and temporary grasslands	Nitrogen limit : 60 kg per ha Animal density limit : 1.4 livestock units per ha Mowing dates: After May first
– Alfalfa	Mowing forbidden between May 15th and July 31st Pesticide spraying forbidden between 1st April and 15th November Irrigation forbidden
AEP fixed private transaction costs	175 €/farm for the 5-year contract
AEP variable private transaction costs	4% of the AEP compensation payment
AEP public transaction costs	724 €/farm taking up the AEP for the 5-year contract

Table 3.1
Characteristics of the agri-environmental programme to ensure Little Bustard conservation.

rate to compute the gross margins of LBF crop rotations. The private and public transaction costs related to the agri-environmental programme have been accounted for (see Table 3.1). Private transaction costs are divided into fixed costs per farm corresponding to the time spent to gather information, to apply for AEP and for monitoring; and into variable costs per hectare enrolled, corresponding to the time spent for reporting to the administration and auditing. These values are taken from Peerlings and Polman (2004, 2008), and are in accordance with Falconer (2000). Public transaction costs correspond to the time spent to advertise for the AEP, to negotiate, contract and monitor (Falconer et al, 2001)[6].

[6]Information on time spent administrating the contracts was provided by the Direction Départementale de l'Agriculture (Departmental Agricultural Services) of the département des Deux-Sèvres, the local public service in charge of agri-environmental programmes. It is composed of half a day per year (times 5 in our case) for the control, plus 1.5 days for contract administration and 1 day for information and negotiation for the entire 5-year period. We therefore took the cost to be 1 week of work for a civil servant in charge of the administration of contracts. Public transaction costs will vary depending on the implementation, i.e., regulation, uniform or differentiated incentive payments. Unfortunately, we did not have data to account for these differences.

3.3.4 Validating the model

To validate our model we first compared farm results to the observed 2005 data-the year for which we have farm type data. We then compared the stylised area land use to the observed 2003 situation-the year for which we have the Natura 2000 site land use. The validation scenario entails maximising the gross margin of each farm, given the current LBF agri-environmental payments for enrolled fields. We compared our crop farms' simulated land use to data for farms growing cereal, oilseed and protein crops[7] provided by the French agricultural bureau of statistics (Enquête Structure 2005[8]) at the department level, which is the smallest administrative level for which data are available. Cereal crops represent 65.7% of land in the validation scenario and 58% in the observed situation. Oilseed and protein crops, taken together, represent 24.3% and 35% respectively. We validated the behaviour of mixed dairy farms by ensuring that our characterisation was consistent with the characteristics of the mixed dairy farm types described by the French Breeding Institute (Institut de l'Elevage) and reflecting the different local livestock orientations [9]. Farms were discriminated according to 4 criteria: the share of cash crops in the utilised agricultural area, the share of maize in the fodder crops area, the area in grassland per livestock unit, and the share of grazing in the feed ration. In the model, five farms out of six behave as "forage stocking-based" farms, for which feed rations mostly depend on maize silage and dried fodder, representing, over a year's time, at least 75% of them. Maize represents at least 34% of the total area dedicated to fodder crops. One farm behaves as a "pasture-based" farm, which relies mostly on grazing (grazed grass is the exclusive feedstock for at least 8 weeks per year, and fodder maize represents less than 23% of the total fodder crop acreage). Finally, we compared our stylised area simulated land use to the observed one involving the Natura 2000 site in 2003 [10]. Table 3.2 shows that they are quite similar. The LBF managed grassland fields, obtained in the case of the validation scenario, covers 5% of the stylised area (Fig. 3.4). This result is consistent with the share of Natura 2000 acreage actually contracted under the LBF AEP in Poitou-Charente (7 500 ha of the 142 655 ha, i.e., 5.2% [11]).

In addition, only mixed dairy farms take up to the scheme, enrolling on average

[7] I.e., Type of Farming 13, in accordance with FADN classification : http://ec.europa.eu/agriculture/rica/detailtf_en.cfm

[8] http://agreste.maapar.lbn.fr/ReportFolders/ReportFolders.aspx , " STRU005 "

[9] http://www.inst-elevage.asso.fr/html1/IMG/pdf_CR_080755002.pdf. It was not possible to use the French agricultural statistics at the département level, for mixed dairy farms were aggregated with other FADN "Types of Farming".

[10] The 2003 land use is the only one available.

[11] http://www.outarde.lpo.fr/images/fich48847aea5d97e-PlaqOutarde.pdf

Land use	Natura 2000 site (2003 data)	Stylised area (simulation for 2005)
Cereal crops (excl. Maize)	37%	48.6%
Oilseed crops	21%	22%
Maize (incl. Silage)	15%	12.2%
Grasslands	13%	8.1%
Protein crops	2%	
Set-aside	9%	90%
Other	3%	

Table 3.2
Actual land use of the Natura 2000 site in 2003 and simulated land use of the stylised zone for 2005.

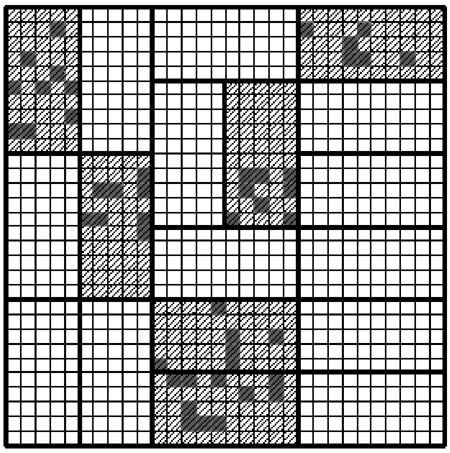


Fig. 3.4. LBF managed grassland fields location obtained within the validation scenario.

15% of their area in the conservation programme. These results correspond well to the situation observed in the field, where only very few crop farms participate in the existing AEP, and the average share of the mixed farms enrolled in the programme does not exceed 20% of their land (between 12% and 20% in our case). It is noteworthy that in the validation scenario using the actual agri-environmental payments, the area under conservation programme has too few hectares and an overly-aggregated spatial pattern in comparison to Little Bustard requirements.

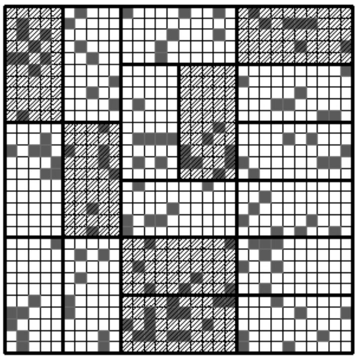
3.4 Simulations and Results

3.4.1 Investigation into the trade-offs between the LBF-managed grassland pattern and its cost

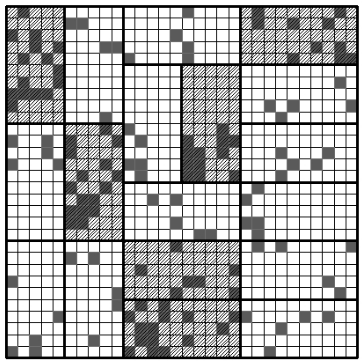
Our first objective was to find the solution that minimizes the cost of a given conservation objective, which in our case requires that 15% of the area under study be covered with LBF managed grassland fields randomly distributed for any radius r ranging from 100m to 1000m. To that end, two additional constraints have to be introduced into the model: one for the total amount of area required and the other for its spatial pattern. We therefore imposed a minimum of 15% of LBF managed grassland in the stylised area. We did not however explicitly include the Ripley index L(r) in the model, since complex non-linearities, together with a high number of binary variables, do not make it possible to solve the problem within an optimization framework. As a consequence, we had to approximate the cost-minimizing effective spatial pattern by a proxy constraint, obliging all farms to dedicate 15% of their land to Little Bustard conservation, which still represents an effective solution from the environmental point of view (i.e., which meets the conservation requirements). We then investigated the trade-offs between the spatial pattern of land to conserve and its cost, the conserved area being equal, by relaxing this proxy constraint. We found that in the case given here, the suitable spatial distribution for bird conservation can be obtained through a constraint requiring that all farms contribute equally to the conservation programme, each enrolling 15 % of their land (scenario 1C). The generated landscape and the corresponding function values are depicted in Fig. 3.5(a) and Fig. 3.6 respectively. They are put to work as a benchmark for the analysis to follow [12].

The cost of the suitable spatial pattern for conservation-calculated as the difference between the total gross margins (including private transaction costs) obtained without and with size and shape requirements, plus the public administration costs-is 194 060 €. This represents 7% of the total unconstrained gross margin. The cost for the total land required for conservation is then 479 €/ha on average; however, this differs from farm to farm, depending on the farm type and soil quality. Mixed farms on shallow plain soils have the lowest average foregone profit: 81 €/ha. They manage a part of their grassland according to LBF practices even in the absence of a conservation programme. The expansion of these management practices to a few additional hectares does not

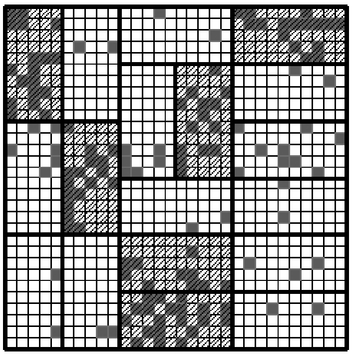
[12]More precisely, Fig. 3.5(a) and Fig. 3.6 represent the solution for the first year of the 11-year period. The spatial pattern of LBF managed fields will change within each farm over time. However, tests carried out for the other years show that the L-values for all of them are close to one another.



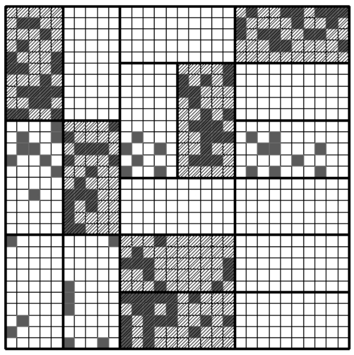
(a)



(b)



(c)



(d)

Fig. 3.5. Suitable spatial pattern for Tetrax tetrax conservation (a); and spatial pattern obtained when the minimum share of each farm to be enrolled in the conservation programme is set at: b) 10%, c) 5% and d) 0%.

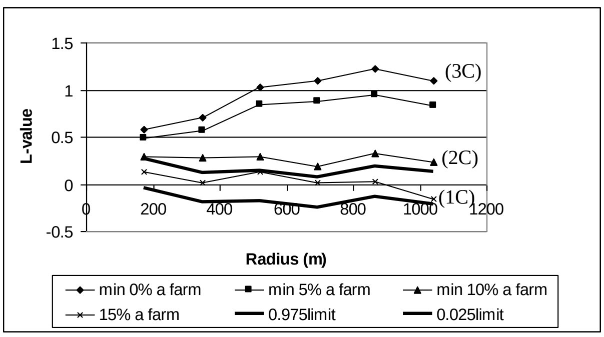


Fig. 3.6. L-function values for the suitable (random) spatial pattern for Tetrax tetrax conservation and for the spatial patterns obtained with different minimum shares of each farm to be enrolled in the conservation programme.

require major changes in the dairy herd size or structure: there is only a small decrease in the cropland area (around 8 %) for a 23% increase in grassland and alfalfa area. Overall, that gives rise to a higher proportion of "grass" fodder and grazing in feed rations, substituting for maize silage, together with a slight decrease in purchases of concentrated feedstock. Crop farms on very fertile deep plain soils have an average foregone profit higher than 780 €/ha of LBF managed grassland. They substitute cash crops with alfalfa and temporary grassland, which makes them lose 13% of their gross margin even though they are allowed to sell their alfalfa. In general, the average foregone profit does not exceed 148 €/ha of LBF managed grassland in the case of livestock farms, and it does not fall below 585 €/ha in the case of crop farms. If the farms that represent a "low-cost" for conservation were allowed to provide a larger part of the required land and the farms representing a "high-cost" for conservation could decrease their share, then the total area for the Little Bustard conservation would cost less. Let us now consider the option [13] to relax the spatial pattern constraint by setting the minimum share to be enrolled in the conservation programme by each farm below 15%. In this case, the rest of the land can be provided by the "low-cost" farms. Fig. 3.5 (b)(c)(d) shows how the location of land for conservation changes when we oblige each farm to enrol at least 10% (scenario 2C) or 5% of its land, or when there is no minimum participation required (scenario 3C, i.e., minimum 0% per farm, Fig. 3.5(d)). Fig. 3.6 shows how the spatial pattern deteriorates (aggregates) as the minimum share to be enrolled by each farm decreases. The pattern of land for conservation associated with scenario 2C can be considered almost "suitable". The annual cost of the total land under conservation decreases to 169 696 €, 154 445 €, and 149 101 € if the minimum participation constraint is set to 10%, 5 % and 0% of each farm, respectively. Private transaction costs represent circa 5% of farmers' total conservation cost. They do not really impact farmers' participation in the AEP, as the fixed transaction cost per farm never exceeds 2% of the total conservation cost.

3.4.2 Policy simulations

In this section, the model is used to test farmers' responses to various agri-environmental schemes and to set up contract schemes which would make it possible to reach or approach as nearly as possible, the suitable spatial pattern 1C, presented in Section 3.4.1. Implementing the effective reference solution 1C supposes that we have complete information about each farm, and thus can go to each farmer and propose to him/her a

[13] We also tried to relax the "15% a farm" constraint by setting a maximum participation level above 15%. It did not perform better than the minimum participation constraint, neither in terms of pattern quality nor in terms of conservation cost.

contract which determines the area he/she should enrol, as well as the payment which would precisely compensate him/her for the cost of the LBF managed grasslands. However, the cost of gathering information on this precise compensation payment for each field and the negotiation with each farmer would probably make the implementation of the scenarii 1C and 2C too costly in the real-life situation. Therefore, agri-environmental schemes usually propose a uniform, non-differentiated across-farm payment, per hectare of LBF managed grassland to all farmers while letting farmers choose the area they wish to enrol. Using the model, we calculated that a payment of 690 €/ha would be necessary if all the farmers are to enrol 15% of the overall farmland in the LBF agri-environmental programme. This would therefore cost 280,941 €[14] (scenario 3P). However, the resulting spatial pattern is highly aggregated and thus not acceptable (see Fig. 3.7). This scenario is equivalent to scenario 3C, where only the total area for conservation is constrained, at the level of the area under study. The contract scheme able to ensure the "almost suitable" pattern for conservation, 2C, would require a slightly more complex structure. We found that both a payment of 810 €/ha, for up to 10% of a farm area, and an additional payment of 450 €/ha, above this limit, are necessary (scenario 2P). The cost of this programme, which leads to an "almost suitable" land pattern (see Fig. 3.7), is 282,056 €. Finally, even the suitable reference pattern 1C can be obtained when paying both 810 €/ha for up to 14% of each farm area and an additional 220 €/ha over and above this limit (scenario 1P), for a programme costing 314,726 €. Public administrative costs are higher in scenario 1P and 2P compared to scenario 3P, as more farms take up the AEP. However, they never exceed 1% of the total programme budget.

3.4.3 Comparison of conservation costs with the budgetary costs of policies

The cost of the land to come under conservation measures (generated in Section 3.4.1) and the budgetary cost of the corresponding programmes (simulated in Section 3.4.2) are compared in Fig. 3.8. We can see that the latter is always at least 62% higher than the former; the reason being that agri-environmental payments are not differentiated between farmers and thus "low-cost" farms are overcompensated. The sum of total payments necessary to implement the "almost suitable" pattern obtained in 2P is only 0.14% higher than the sum of the uniform payments in 3P, whereas the difference in the conservation cost between the corresponding patterns 2C and 3C is 13.8 %. This difference means that the way a conservation measure is implemented is also to be considered when weighing

[14] Compensation payments plus public administration costs.

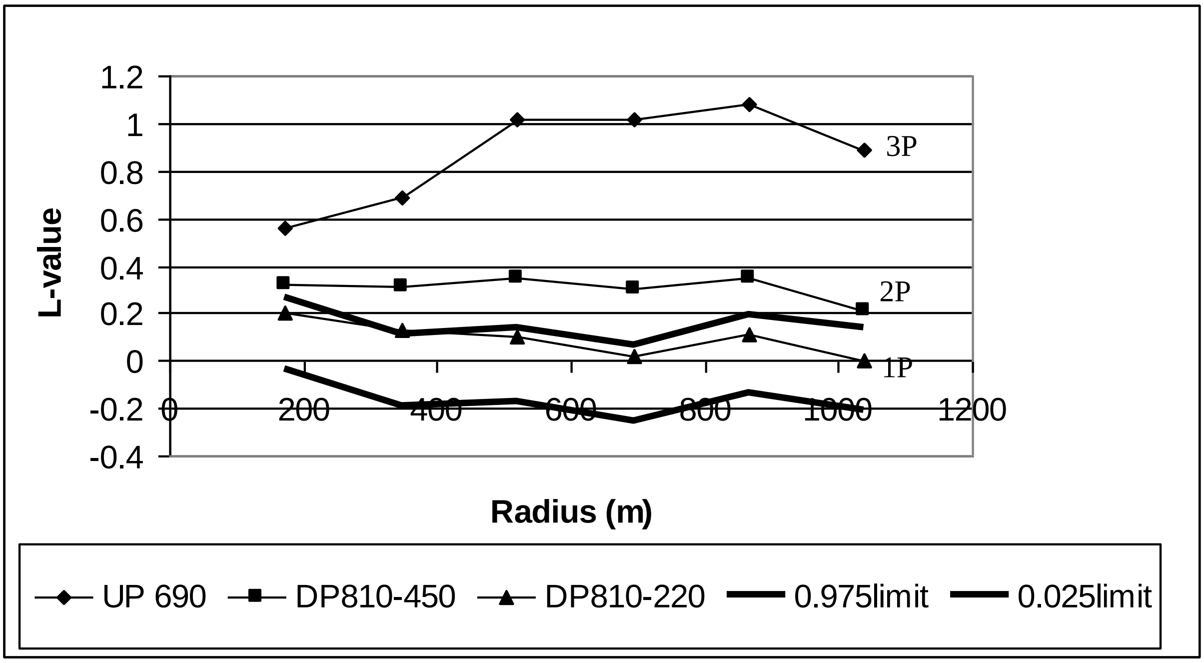


Fig. 3.7. L-function values for uniform (3P) and degressive (1P and 2P) payment schemes.

the costs against environmental benefits. Depending on the institutional arrangement (e.g., perfect discrimination versus single uniform contract), the difference in costs can be quite different for the same change in the environmental outcome. If farmers did not have the possibility of selling their alfalfa fodder, the necessary compensation payments would be substantially higher; e.g., the uniform payment necessary to have 15% of the land enrolled in the AEP would rise from 690 € to 867 €, i.e., by 25%. This is due to the fact that the average foregone profit for crop farms would rise by 43%, as they can neither use nor sell the alfalfa fodder. In addition, the total conservation cost in Section 3.4.1 would rise by 13% to 33%, depending on the minimum area to be enrolled in the programme by each farm. The existence of a market for alfalfa therefore improves the participation and decreases the cost of the programme.

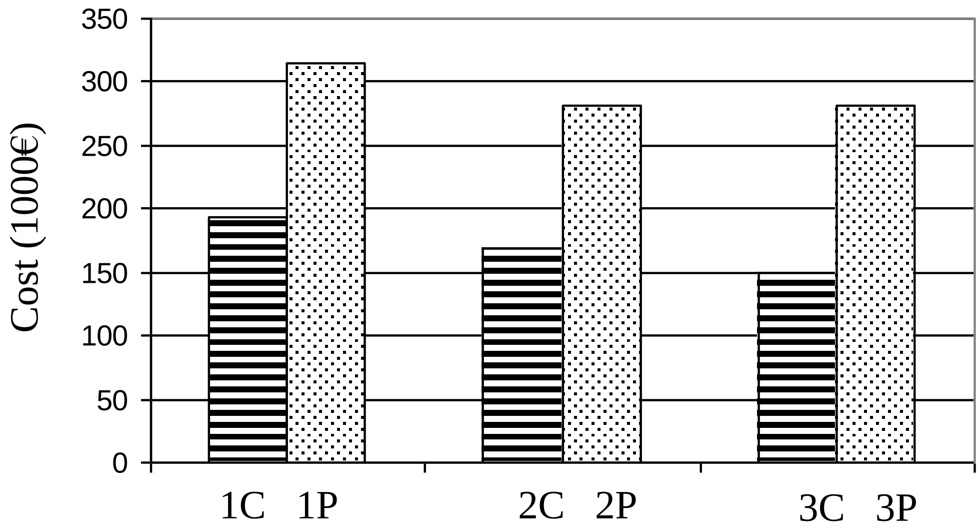


Fig. 3.8. Cost of the conservation measures (scenarios 1C, 2C, and 3C) and of the equivalent agri-environmental programme (policy simulations 1P, 2P, and 3P) for different schemes, including public administrative costs.

3.5 Conclusion

This paper addresses the issue of designing policies for habitat conservation on agricultural land, in the cases which require a non-aggregated spatial distribution of the fields enrolled into an a gri-environmental programme. To analyse the design and implementation of an agri-environmental programme aimed at Little Bustard (Tetrax tetrax) conservation in the Plaine de Niort, France, we present a spatially explicit mathematical programming farm-based model which accounts for three spatial levels (field, farm and landscape), associated with a relevant spatial pattern index (the Ripley L function). Results show that valuable insights into agri-environmental programme design are gained through a detailed representation of farming system management.

The cost and spatial pattern of the land to come under the conservation programme depend on the participation level of the different farm types. The suitable spatial pattern for the Little Bustard conservation, which requires having Little Bustard-friendly (LBF) managed grassland plots randomly distributed across the area under study, is the most costly one because it tends to require equal participation of all, that is to say "low-cost" as well as "high-cost" farms. Allowing for a higher percentage of the total land required for conservation to be made up of "low-cost" mixed dairy farms, on less fertile soils, decreases the cost of conservation; however, the spatial pattern becomes aggregated and is less suitable for conservation purposes. It is possible to achieve a spatial pattern close to the suitable one but less costly if each farm is required to enrol at least a small area in the LBF AEP. The policy simulations revealed that the various spatial patterns of land under the conservation programme can be obtained through relatively simple uniform contract structures which do not require complete information about, and negotiation with, individual farmers. An effective contract structure, which encourages all farms to enrol at least a small share of their land in the programme, entails a set of two payments whereby one of them is guaranteed up to a certain share of the farm, and the other, much lower one, remunerates all the land enrolled above this limit.

Although we see, thanks to the simulations, that the sum of the payments necessary to obtain a given pattern within agri-environmental schemes is always higher than the actual cost of that pattern by at least 62%, the two-payment scheme seems relatively efficient in terms of budgetary expenditure, since this option costs nearly the same as a uniform single payment scheme (which gives rise to an unsuitable, aggregated pattern) but can provide considerably better spatial patterns.

Our modelling approach, which takes simultaneously into account farm behaviour and landscape pattern, contributes to the design of agri-environmental programme when the spatial location of conservation measures matters. However, the research could be extended along several lines. Firstly, we do not account for differences in farm size or farm plot distribution so as to better assess the impact of soil heterogeneity between farms on their participation in the conservation programme and the location of fields that could be enrolled. However, we are aware that these farm characteristics will influence the design of the payment scheme. Hence, further research is needed to extend this work to other situations where either i) only a few large farms operate in the given area or ii) the fields of individual farms are not contiguous but rather dispersed across the landscape, because in those situations the proposed two-payment scheme could easily result in a highly aggregated land pattern. Secondly, in this study we focus on the agri-environmental contract type widely enforced in France and in the E.U., i.e., a uniform subsidy per hectare of land managed according to an environmentally-friendly practice. However, other incentive-based instruments, that have potential to decrease the budgetary expenditures of or improve the spatial allocation of fields enrolled in the conservation programme, do exist. For instance, auction schemes or an agglomeration malus (inspired from the agglomeration bonus used by Parkhurst and Shogren, 2008 and Parkhurst and Shogren, 2007) should be further investigated.

3.A Appendix. Ripley K and L Functions

3.A.1 Interpretation of K(r)

Let A be the area of the zone under study, N the number of observed plots to conserve, and λ the density ($\lambda = N/A$). We have seen in Section 3.2.2 that $\lambda \cdot K(r)$ can be interpreted as the expected number of further LBF managed grassland plots within a radius r of any arbitrary plot. If conservation plots are randomly distributed within a given radius r, then the expected number of such plots within this radius is equal to $\lambda \cdot \pi r^2$ and $K(r)$ has an expected value of πr^2. The density in the area under study is a given, thus increases when conservation plots are aggregated at radius r (more neighbours) and decreases when such plots are over-dispersed (less neighbours). In our study, the Little Bustard conservation requires a random distribution of LBF grassland plots, therefore a desirable expected value for $K(r)$ is πr^2 .

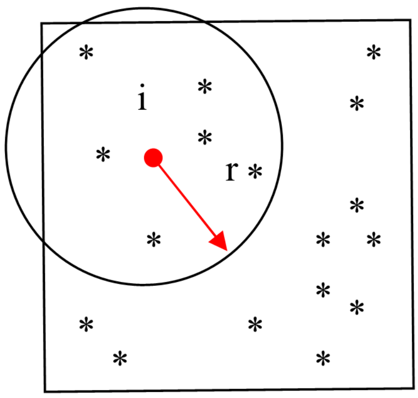


Fig. 3.9. Illustration of the computation of $\hat{K}(r)$ in a given zone of area A with N plots (*) to conserve.

$\hat{K}(r)$ is an unbiased estimator of $K(r)$. It counts the number of neighbouring conservation plots located within a circle of radius r centred on each conservation plot in the given zone (see Fig. 3.9), takes the average and divides it by the conservation plot density in the given zone:

$$\hat{K}(r) = \frac{1}{\lambda N} \sum_{i} \sum_{j \neq i} \Big(w_{i,r} \cdot I_r(d_{i,j}) \Big) \tag{3.8}$$

where $d_{i,j}$ is the distance between two LBF managed grassland plots, I_r a binary variable equals to 1 if $d_{i,j} \leq r$, or to 0 otherwise, and $w_{i,r}$ an edge-effect correction weighting factor. This weighting factor is inspired by the work of Getis and Franklin (1987) cited in Haase (1995). It is based on the assumption that the density and distribution pattern of neighbouring areas outside and inside the studied zone boundaries are the same:

$$w_{i,r} = \frac{circlearea(\pi r^2)}{circleareawithinstudiedzoneboudaries} \tag{3.9}$$

3.A.2 Test of the hypothesis of Complete Spatial Randomness

According to Haase (1995), $\hat{K}(r)$ is calculated for the relevant values of r and is tested against the hypothesis of Complete Spatial Randomness (CSR of Diggle, 1983). As mentioned in Section 3.2.2, we preferentially apply the normalised form of $\hat{K}(r)$, i.e., $\hat{L}(r) = \sqrt{\frac{\hat{K}(r)}{\pi}} - r$, which has an expected value of zero under the null hypothesis of CSR. We use the Monte Carlo method to create a 95% confidence envelope and test $\hat{L}$ against the null hypothesis of CSR. To that end, we simulated N randomly-generated conservation fields following a Poisson distribution on the map of the given area and we calculated the $\hat{L}$ function for the same set of radii as the one used in the scenarios. We repeated the procedure a thousand times and defined the bounds of a 95% confidence envelope for $\hat{L}(r)$.

Chapter 4

Agri-environmental policies for biodiversity when the spatial pattern of the reserve matters

Abstract

The aim of this paper is to compare different environmental policies for cost-effective habitat conservation on agricultural lands, when the desired spatial pattern of reserves is a random mosaic. We use a spatially explicit mathematical programming model which studies the farmers' behavior as profit maximizers under technical and administrative constraints. Facing different policy measures, each farmer chooses the land-use on each field, which determines the landscape at the regional level. A spatial pattern index (Ripley L function) is then associated to the obtained landscape, indicating on the degree of dispersion of the reserve. We compare a subsidy per hectare of reserve with an auction scheme and an agglomeration malus. We find that the auction is superior to the uniform subsidy for cost-efficiency. The agglomeration malus does better than the auction for the spatial pattern but is more costly.

4.1 Introduction

In many regions, agricultural lands host a significant share of biodiversity including common and emblematic species. Over the last fifty years however, farmed landscapes have experienced dramatic changes, mainly due to the intensification of farming techniques and increases in the size of agricultural fields. As a result, natural habitats have been transformed and fragmented, leading to many species' decline (**?**Chamberlain et al., 2000).

Common farmland birds in Europe, for instance, have declined by 25% since the 1980's (Gregory et al., 2005).

In farmlands, dominated by private ownership, providing sufficient incentives to landowners to preserve biodiversity is essential. Agri-environmental policies have progressively been introduced for example in Europe (eg. Natura 2000) and in the United States (eg. the Conservation Reserve Program) to preserve habitats. In designing these policies, the economic issue lies in the trade-off between environmental effectiveness and economic costs (opportunity costs[1], compensation payments to farmers, transaction costs). The environmental result depends on the size of the protected area but also on the spatial configuration of this area. A habitat reserve[2] of a given size does not have the same ecologic impact when reserve sites are fragmented, agglomerated or distributed as a random mosaic. The best spatial pattern depends on the considered species: the grizzly bear would prefer an agglomerated reserve for instance whereas a black-footed ferret survives better on dispersed reserves (see Parkhurst and Shogren, 2008; see also Soule and Simberloff, 1986 for insights on the famous SLOSS debate: Single Large or Several Small reserves).

The aim of this paper is to compare different policy instruments for cost-effective habitat conservation on agricultural lands, when the desired spatial pattern of the reserve is a random mosaic. This spatial pattern is adapted to certain threatened bird species that breed on agricultural lands, such as the Little Bustard (*Tetrax tetrax*), an Annex 1 species of the European Union Birds Directive (79/409/EEC). Note that most contributions on the spatial configuration of the reserve are concerned with avoiding fragmentation, which is harmful to many species. However, on agricultural lands, where land-uses are generally spatially aggregated due to aggregated land qualities, natural habitats are often aggregated. Therefore, examining the best policies to protect species that inhabit agricultural lands and need to disperse to reserve is a new and useful topic.

Many studies have been devoted to optimal reserve design, mainly in the field of conservation biology (see Williams et al., 2005, for a general review; see Wossink et al., 1999, and van Wenum et al., 2004, for a more specific analysis on agricultural lands). These contributions have focused on the question of where the reserve should be located to adequately (and cost-efficiently[3]) protect the biodiversity. However, they do not address

[1]The opportunity costs of habitat conservation can be defined as the forgone profits due to setting aside lands instead of implementing a more profitable land-use.

[2]We define here the "reserve" as all sites characterized by environment-friendly land-uses and management options. In our case, the reserve can thus include some agricultural land-uses (eg. grassland).

[3]An extension of the basic literature to the field of economics has consisted in incorporating land costs (Polasky et al., 2008; Naidoo et al., 2006; Hamaide and Sheerin, 2011).

the question of how to reach this optimal reserve. They implicitly assume that the social planner has perfect knowledge on landowners' characteristics and selects reserve sites minimizing opportunity costs. Unfortunately, governmental agencies have imperfect information on private costs and cannot implement the first-best reserve location in a direct way (Lewis et al., 2009).

Designing incentive-based conservation policies, aiming at a cost-efficient reserve under information asymmetries, is thus a further step. Many economic articles have examined this issue using mechanism design theory but without taking into account the spatial characteristics of the conserved area (see Ferraro, 2008 for a survey). Recent contributions have introduced the spatial aspects. Lewis and Plantinga (2007); Lewis et al. (2009) and Lewis et al. (2011) study incentive-based policies to reduce habitat fragmentation. These authors use an econometric model to estimate the farmers' decisions (land-use conversion probabilities based on past observations) but do not model the farmers' behavior. Wätzold and Drechsler (2005); Drechsler et al. (2007); Hartig and Drechsler (2009) and Drechsler et al. (2010) ingeniously combine an economic and ecological model to assess various conservation policies. However, they consider exogenous costs for land conservation and do not detail the process explaining these costs (which depend on the landowners' optimal decisions given agricultural prices and yields as well as technical and institutional constraints). Smith and Shogren (2002); Parkhurst et al. (2002); Parkhurst and Shogren (2008); Reeson et al. (2011) and Williams et al. (2012) use experimental economics to see whether rational individuals can achieve the desired spatial pattern of reserve or to test various ecological metrics, but they do not look into the mechanism that drives the farmers' decisions.

We use an economic mathematical programming model (OUTOPIE) which simulates the farmer's behaviour as a profit maximizer under technical and administrative constraints. This leads to land-use choices at the field level and eventually generates a landscape at the regional level. A spatial pattern index (Ripley L function) is then associated to the obtained landscape, indicating the degree of dispersion of the reserve. See Bamière et al. (2011) for a detailed description of the OUTOPIE model.

Mathematical programming farm-level models have largely been used to assess the efficiency of agri-environmental policies (Wossink et al., 1999; Falconer and Hodge, 2001; van Wenum et al., 2004; Havlik et al., 2005; Mouysset et al., 2011). Our model differs in that it takes into account, in addition to the farm-level, both the field and landscape levels, linked to a spatial pattern indicator. As explained above, taking into account these three spatial levels is essential when analyzing biodiversity conservation: the field is the elementary unit of the spatial pattern, the farm is the landowner's decision level, and the resulting landscape level determines the ecological result.

Our model is applied to a Natura 2000 site in France (*Plaine de Niort*), which aims at protecting the Little Bustard. This bird relies exclusively on insects found in temporary grasslands, and preferentially breeds in an arable landscape consisting of a mosaic of alfalfa, grasslands and annual crop fields (Wolff et al., 2001). Its conservation therefore implies a random mosaic of extensively managed grasslands and annual crops. While contiguity and connectivity have been studied, to the best of our knowledge Bamière et al. (2011) was the first attempts to account for a random mosaic distribution of the reserve.

While Bamière et al. (2011) use the OUTOPIE model to investigate the suitable allocation of reserve patches and whether a subsidy per hectare of reserve reaches it, we introduce other policy instruments. We compare three instruments - a subsidy per hectare of reserve, an auction scheme and an agglomeration malus - to reach a given percentage of land enrolled in the reserve. The comparison is based on two main criteria: the spatial criterion (reserve patches must form a random mosaic) and the cost criterion (including opportunity costs, public costs and administrative costs).

The auction scheme works as a procurement auction where farmers indicate the minimum payment they wish to receive to convert one parcel of their land to reserve[4]. The public regulator selects the lowest amount and pays it to the winning farmer against his commitment to convert one parcel to reserve. By favoring competition among farmers, this instrument improves cost-efficiency even when the regulator does not have detailed information on the individual opportunity costs. Empirical studies have demonstrated that cost reductions through conservation auctions can be substantial (Stoneham et al., 2003; Schilizzi and Latacz-Lohmann, 2007). This instrument has increasingly attracted the attention of economists (Latacz-Lohmann and Van der Hamsvoort, 1997, 1998; Latacz-Lohmann and Schilizzi, 2005; Saïd and Thoyer, 2007; Glebe, 2008) . This literature however, based on decision theory, usually simplifies bidders' behavior by assuming an exogenous threshold above which bids are not accepted. One of our contributions is the use of auction theory based on game theory, allowing more realism and precision in modeling the bidders' behavior (McAfee and McMillan, 1987; Klemperer, 1999).

The agglomeration malus is an instrument which accounts for the spatial issue. It consists of a subsidy per hectare of reserve completed with a malus (i.e. a reduction of the payment) when the additional reserve site is adjacent to another reserve site. This malus is

[4]A procurement auction is a type of auction where there are multiple sellers and one central buyer, here the public agency (Fudenberg and Tirole, 1991).

relevant in cases, such as ours, where the desired pattern of the reserve is dispersed. Some authors have examined a similar instrument, an agglomeration bonus (which is relevant when the desired pattern is agglomerated), using experimental economics (Parkhurst et al., 2002; Parkhurst and Shogren, 2007, 2008) and bio-economic modeling (Drechsler et al., 2010).

The rest of the article is structured as follows. First, we present our modelling approach and our method in comparing policy instruments. Then, we introduce an auction scheme and compare it to the subsidy per hectare. Next, we study the agglomeration malus and compare it with the two other instruments. Conclusions and scope for further research are given in the last section.

4.2 The mathematical programming model

OUTOPIE is a mixed integer linear programming model which accounts for three spatial levels: the field, the farm and the region. Fields are characterized by their soil type, irrigation equipment and the farm to which they belong. This determines the agricultural activities and cropping techniques that can be chosen on each field, as well as the resulting yield and gross margin. The farmer makes the decisions concerning land allocation, taking into account policy constraints (e.g. milk quotas and obligatory set-aside) and technical constraints (e.g. feed requirements). Spatial relationships between fields, constituting the landscape, are accounted for at the regional level.

The model includes the major crops in the considered area (wheat, winter barley, sunflower, rapeseed, maize, and sorghum), permanent and temporary grasslands, including alfalfa, and set-aside lands. The reserve is defined here as all lands covered with alfalfa and temporary or permanent grassland, managed in an environment-friendly way[5].

The model maximizes the sum of farms' gross margins including incomes and costs due to the participation in an agri-environmental program, subject to field, farm and landscape level constraints. This is represented in program (4.1), where X^f is the matrix of farm f's activities. $X^f_{i,r}$ are variables of the matrix X^f that indicate whether field i is enrolled in reserve type r (i.e. in one of the environment-friendly managed grassland). There are equal to the size of field i when i is enrolled in the reserve and to 0 otherwise. Π_f is the farm's gross margin from agricultural activities; cp_r is the per hectare compensation payment for an enrolment in reserve type r; vtc_r is a variable transaction cost per hectare of reserve; ftc is a fixed private transaction cost for program participation and RP_f is a

[5]We define here an environment-friendly management as a Little Bustard-friendly management, characterized by restrictions on livestock density, fertilization, pesticides, and mowing dates.

binary variable equal to 1 if the farm participates in the agri-environmental program.

$$\max \sum_f [\Pi_f(X^f) + (\sum_{r,i}(cp_r - vtc_r)X^f_{i,r} - ftc)RP_f] \tag{4.1}$$
$$s.t. Field(X^f), Farm(X^f), Landscape(X^f)$$

This model is applied to a Natura 2000 site located in *Plaine de Niort*, in Poitou-Charente, France. This area was traditionally dedicated to mixed farming but has recently undergone a rapid specialization in crop production, threatening some populations of birds such as the Little Bustard (*Tetrax Tetrax*). The whole Natura 2000 site is about 20 000 hectares (ha) but we have chosen to concentrate on a restricted stylized area of 2 700 ha divided into 900 fields of 3 ha each (see Fig. 4.1). There are three main groups of soils in *Plaine de Niort* - calcareous valley, deep and shallow plain soils - with different agricultural potentials. They are represented on the grid (Fig. 4.1) according to the ratio and layout observed. We considered 12 crop growing farms and 6 mixed dairy farms, both types being located on all types of soils and some of them having the possibility to irrigate a fixed set of contiguous fields. More details can be found on the description and the validation of the OUTOPIE model, as well as on the case study, in Bamière et al. (2011).

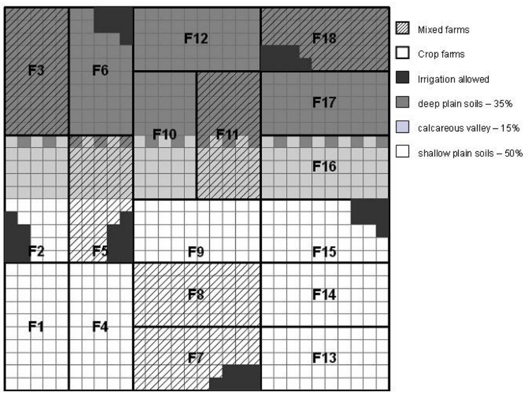


Fig. 4.1. Model representation of the studied area (18 farms; 3 soil types)

In order to account for the spatial pattern of the obtained reserve, the model has been completed with a spatial indicator. According to some ecologist experts (Bretagnolle et al., 2011), the most suitable spatial pattern for the Little Bustard conservation is at least 15% of land covered by extensively managed grassland patches (3 ha being the ideal field size), randomly or regularly located within any radius between 100 and 1000 meters.

As a consequence, we need to measure not only the size but also the shape of the reserve generated by the model. In order to do so, we use an indicator based on Ripley K and L functions (Ripley, 1977, 1981). Theses functions measure both the density of the reserve and the distances between reserve sites. They are widely used in plant ecology (Haase, 1995). Results can be interpreted as follows (see Fig. 4.2 for two spatial distributions of the reserve and Fig. 4.3 for the associated values of the Ripley function L): a) if L remains within the confidence envelop (dotted lines in Fig. 4.3) then the spatial pattern of the reserve is significantly (Poisson) random; b) if L is above the upper limit of the confidence envelop, then the spatial pattern is clustered or aggregated. More details are given on the Ripley indicator in Bamière et al. (2011).

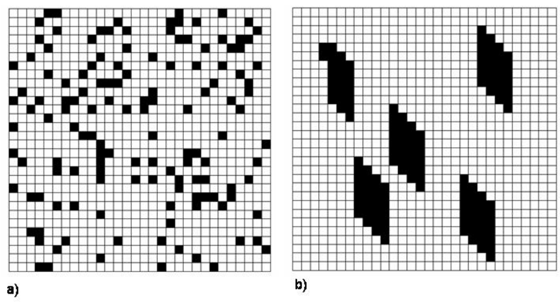


Fig. 4.2. Spatial distribution of 135 reserve plots on a 900 plots grid: a) random, b) aggregated.

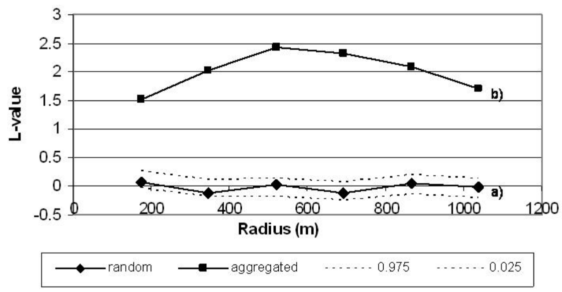


Fig. 4.3. Ripley L function for the random (a) and aggregated (b) distributions

4.3 A comparison of policy instruments

We now use our modelling approach to compare different policy instruments in order to reach a given environmental objective. This objective, consistent with ecologists' recommendation for the Little Bustard, is 15% of land covered with reserve.

The policy instruments are compared according to two criteria. First, we compare the total costs of reaching the 15% objective (cost-efficiency). Second, we examine the spatial configuration of the obtained reserve and whether reserve patches are randomly dispersed (i.e. whether the Ripley function is in the confidence envelop). We have chosen to consider both these criteria independently without giving a priority to one or the other[6].

Regarding the total costs of the policy, we first consider the private costs. These are the sum of the opportunity costs - or forgone profits - incurred by farmers when converting their lands to reserve. These costs are minimized when converting first the less profitable lands, i.e. those with a lower associated gross margin. The three instruments we compare - namely a subsidy, an auction and a subsidy with agglomeration malus - are incentive-based instruments that let the farmers choose which parcels they convert to reserve. As the profit-maximizing farmer always chooses to convert first the cheapest parcels, we can show that total opportunity costs are automatically minimized. Therefore, the minimization of private costs is not a discriminatory criteria among the instruments we study.

We next consider the public costs of the policy. These are defined as the sum of the compensation payments to farmers. We assume we wish to compensate farmers for the opportunity costs of habitat conservation[7]. However, these costs are heterogeneous among farmers (due to different farm types, land qualities, etc) and, generally, the policy-maker does not know each farmer's costs. Moreover, farmers are not willing to reveal their real costs as, by communicating higher levels, they would increase their compensation payment (adverse selection). As a result, the public regulator cannot pay the exact amount compensating the farmers' costs. We will see how some instruments deal better than others with this issue.

The subsidy per hectare of reserve has been studied in Bamière et al. (2011). This instrument reaches the 15% objective with a total public cost of **279 thousand euros**. Total payments to landowners exceed their real opportunity costs due to imperfect

[6] In order to give a priority to one objective or the other, we would have to write a social welfare function including the value for society of this bird's survival and expliciting the way the spatial pattern of reserve affects its probability of survival. This goes beyond the scope of our analysis.

[7] This is consistent with the idea of remunerating them for an environmental service to society.

information (the uniform subsidy is set so as to cover the cost of the most expensive parcel converted to reserve whereas some cheaper parcels have been converted). In total, farmers are compensated about 92% above their real costs, which shows tremendous cost inefficiencies. This can be explained as follows. In order to be cost-efficient, a policy instrument must offer a compensation payment as close as possible to the real costs incurred by the farmer to convert lands to reserve. However, as we have seen, these costs are heterogeneous and when using a uniform payment, payments exceed real costs as the payment must be high enough to cover high-costs reserve, therefore over-compensating low-costs reserves.

Moreover, this subsidy does not reach a suitable configuration of reserves: the Ripley function is outside the confidence envelop (see Fig. 4.5). This is linked to the fact that landowners reserve the parcels that represent the lowest opportunity costs. These opportunity costs are linked to the quality of the land, the farm type (mixed farms vs. crop farms) and/or the possibility to irrigate. These characteristics being partly aggregated (which is common on agricultural lands), the obtained reserve is partly aggregated.

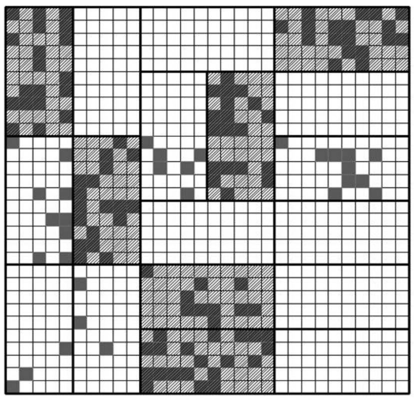


Fig. 4.4. Reserve location with the subsidy per ha

We now consider other instruments that might perform better than the subsidy, either on its cost-efficiency (eg. the auction) or on the spatial objective (eg. the agglomeration malus).

4.4 The auction scheme

Auction schemes have increasingly attracted the attention of policy-makers to deal with agri-environmental regulation with incomplete information. Several real cases exist such as the Conservation Reserve Program in the United States (Kirwan et al., 2005), the

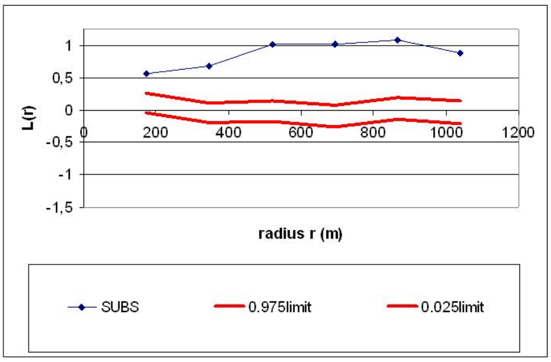


Fig. 4.5. The Ripley L function with the subsidy per ha

Bush Tender in Australia (Stoneham et al., 2003) or some regional experiences in Germany Groth (2005). According to many economists, this policy instrument, by favouring competition among farmers, helps minimize the payments to farmers even though they detain private information on costs (see Cason and Gangadharan, 2004; Taylor et al., 2004; Reeson et al., 2011 and the references given in the introduction).

The auction we study here is a discriminatory-price sealed-bid procurement auction which works as follows. First, farmers submit their bid to the public regulator, i.e. they indicate the minimum payment they wish to receive to accept converting one parcel of their land to reserve. Their bid is sealed, meaning that the other farmers cannot observe it. Second, the regulator selects the best offer, i.e. the lowest amount, and pays this amount to the winning farmer against one additional parcel of reserve on his land. If several farmers bid at the lowest amount, they all win the bidding and receive this amount against one parcel of reserve. The operation is repeated until the total reserve reaches the desired size.

In the literature on auctions in conservation contracts, most contributions are based on decision theory[8] (Latacz-Lohmann and Van der Hamsvoort, 1997, 1998; Rousseau and Moons, 2006; Saïd and Thoyer, 2007; Glebe, 2008). This stream of literature has the advantage of being simple and tractable but its limit lies in the fact that it considers the threshold above which a bid is not accepted as exogenous, rather than resulting from the interaction among bidders. One of the main contributions of this article is that we model bidders' behaviour and derive a formula for the optimal bid of a bidder i based on game theory.

[8]Decision theory examines the decisions of rational individuals facing uncertainty but, contrary to game theory, it does not look into the strategic interactions among these individuals and how these interactions affect their decisions.

We assume there are n farmers. For simplicity, we assume in our demonstration that all farmers are risk-neutral but we can show easily that our results on the auction's performance remain valid in the case of risk-adverse farmers. Let us denote as Π_i^0 the profit of farm i without any commitment on its land-use and Π_i^1 its profit - not including the compensation payment - when farm i signs a contract with the public authority, committing to one additional parcel of reserve on its land. $v_i = \Pi_i^0 - \Pi_i^1$ represents the forgone profit of farm i (or opportunity costs) due to an additional parcel of reserve. Following the basic literature in game theory on auctions (see Klemperer, 1999), we assume that the values v_i are "independent private values", i.e. it is private information for each farmer i and it is common knowledge that each v_i is independently drawn from the same continuous distribution $F(v)$ on $[0, \bar{v}]$, with density $f(v)$. The assumption of independent private values is realistic in our case as opportunity costs are specific to each farm according to their type, land quality and irrigation equipment. Note that the lowest value for v is necessarily 0 as the opportunity cost cannot be negative for rational landowners who maximize their profit.

Given our assumptions, we can prove that the optimal bid of a farmer with opportunity cost v is given by the following formula

$$b^*(v) = v + \frac{\int_v^{\bar{v}} [1 - F(x)]^{n-1} dx}{[1 - F(v)]^{n-1}} \tag{4.2}$$

Proof. The optimal bid of player i of opportunity cost v is the expectation of the lowest of the remaining $(n-1)$ values conditional on all these values being above v. Since the density of the lowest of $(n-1)$ values is $(n-1)f(v)[1-F(v)]^{n-2}$ (expected value of v given that this value is inferior to the $(n-2)$ remaining values), the expectation of the lowest of $(n-1)$ values is

$$\int_0^{\bar{v}} x(n-1)f(x)[1 - F(x)]^{n-2} dx$$

The probability that v is inferior to the lowest of the $(n-1)$ remaining values is then

$$\int_0^{\bar{v}} (n-1)f(x)[1 - F(x)]^{n-2} dx$$

As a result, the optimal bid is

$$\frac{\int_0^{\bar{v}} x(n-1)f(x)[1 - F(x)]^{n-2} dx}{\int_0^{\bar{v}} (n-1)f(x)[1 - F(x)]^{n-2} dx} \tag{4.3}$$

After integrating the numerator by parts and simplifying, this yields formula (4.2). Our methodology is inspired from Klemperer (1999) but adapted to a procurement auction case.

Formula (4.2) describes the farmer's behavior which makes a trade-off between net pay-offs and the acceptance probability. A higher bid increases the net pay-off but reduces the probability of winning, and vice-versa. Each farmer's bid is then equal to his opportunity cost v (first term in (4.2)) plus a margin depending on v (second term in (4.2)). We can actually show that this margin is decreasing in v and we can easily see that for the farmer with the highest opportunity costs, i.e. with type $\bar{v}$, this margin is equal to zero. In other words, it is optimal for bidders to bid above their real costs in order to increase their gains. This phenomenon is amplified for low-costs participants (who can easily bid above their costs and remain competitive), whereas high costs participants are more likely to bid close to their costs in order to remain competitive. As a result, both the subsidy and the auction scheme may induce an over-compensation of farmers compared to their real opportunity costs.

In order to go further, we assume v follows a normal distribution on $[0, \bar{v}]$ with mean $E(v)$ and standard deviation σ. Note that another limit of the current literature on conservation auctions using decision theory is the use of a uniform distribution for the exogenous bid cap above which the bid is not accepted (Latacz-Lohmann and Van der Hamsvoort, 1997). By using here a normal distribution for farmers' types, our model is more realistic as some opportunity costs levels are more common than others, especially at a local scale.

The formula for b^* in the normal distribution case is

$$b^*(v) = v + \frac{\int_v^{\bar{v}} [1 - \int_0^x \frac{1}{\sigma\sqrt{2\pi}} exp(\frac{-(u-\frac{\bar{v}}{2})^2}{2\sigma^2}) du]^{n-1} dx}{[1 - \int_0^v \frac{1}{\sigma\sqrt{2\pi}} exp(\frac{-(u-\frac{\bar{v}}{2})^2}{2\sigma^2}) du]^{n-1}} \tag{4.4}$$

In our model, it has been found that the highest possible value for the opportunity cost (the highest possible difference between the profit without any constraint and the profit when committing to one additional parcel in reserve) is $\bar{v} = 3320$ euros. We can then show through many simulations using Mathematica that, for a wide range of values of σ and v, b^* can be approximated by v, i.e. the second-term in (4.4) tends towards zero with a 10^{-1} precision (i.e. ten euro cents). In other words, in our case, the auction approximately allows to pay farmers at their real cost. This result is due to the value of $\bar{v}$ in our case but it is shown to remain valid for many values for $\bar{v}$, v and σ as long as $\bar{v}$

is not too small[9].

Using this auction model, we introduce this policy instrument in the OUTOPIE model. Auction rounds are repeated until 15% of the zone is enrolled in the reserve. To limit learning effects and collusion among bidders, we assume there is no diffusion of information between two auction rounds (i.e. the amount of the winning bid and the identity of the winner are not revealed). As argued by Milgrom (1987), the advantage of a sealed-bid design is that it is less susceptible to collusion[10].

We find that the auction reaches the 15% objective with a total public cost of **145 thousand euros** which approximately corresponds to farmers' real costs of conversion. The auction therefore reaches a much better cost-efficiency than the subsidy, which was almost twice more expensive. This is due to the fact that as explained above, in our case, the auction is approximately cost-efficient.

Regarding the spatial configuration of the reserve, the auction does not reach the desired pattern (see Fig. 4.7 where the Ripley function is shown to be outside the confidence envelop). As with the subsidy, the reserve is found to be partly aggregated in the auction scheme due to the aggregation of low-cost parcels. Let us now look into another policy instrument that explicitly takes into account the spatial issue.

4.5 The agglomeration malus

For many species, the spatial configuration of the habitat reserve - and not only its total size - is crucial for survival. There is no scientific consensus on the optimal spatial pattern of the reserve (which depends on the species) and only very few policy instruments have been developed to take into consideration these spatial issues. In the emerging literature on the topic, the most recurrent objective is to avoid reserve fragmentation. Parkhurst et al. (2002) and Parkhurst and Shogren (2007, 2008), for instance, examine an incentive

[9]For example, the threshold value for $\bar{v}$ above which bidders' margin is insignificant is $\bar{v} = 22$ when $\sigma = 500$ and $v = 0.5$. It is even lower for higher values for v. More details regarding these simulations are available upon request.

[10]In multi-unit auctions or repeated auctions, there is a risk of collusion among bidders (Klemperer, 1999). That is, if communication is possible and easy among farmers, they may agree to increase simultaneously their bid in order to improve their gain, which reduces the cost-efficiency of the auction for the public agency. However, bidders are also competitors and may be tempted to deviate from this type of agreement in order to lower unilaterally their bid and win the conservation contract (prisoners' dilemma). The literature in game theory shows that in a repeated game with finite horizon, the prisoners' dilemma persists and cooperation among players to collude is not stable (Fudenberg and Tirole, 1991). Moreover, bids are sealed in our case, limiting the diffusion of information among bidders. As a result, we assume that no collusion occurs although the game is repeated. There may be, however, some learning effects due to the fact the auction is repeated; this has been studied in experimental economics (see Reeson et al., 2011) and remains an interesting scope for further research.

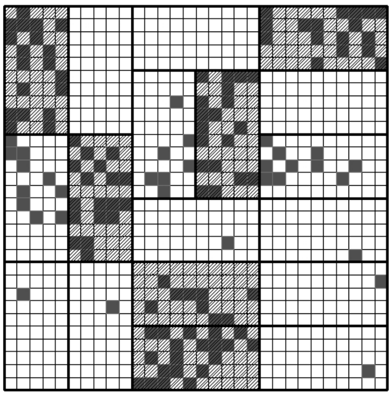


Fig. 4.6. Reserve location with the auction scheme

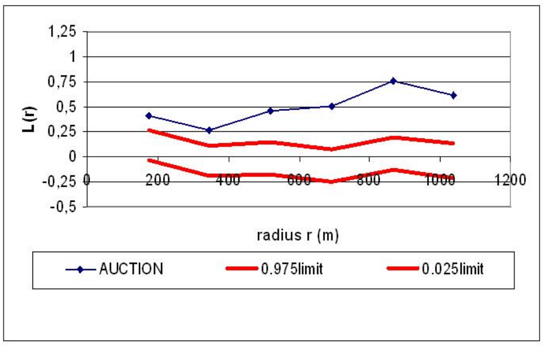


Fig. 4.7. The Ripley L function with the auction scheme

mechanism called an agglomeration bonus, which awards landowners bonus payments for the conservation of adjacent parcels[11]. These authors use experimental economics to examine whether players are able to coordinate and reach the desired spatial configuration of land when facing such an agglomeration bonus.

We focus here on a similar instrument but reversed - an agglomeration malus - given that, on agricultural lands, it may by useful to avoid a too aggregated reserve, harmful to certain species such as the Little Bustard. Note that Parkhurst and Shogren (2007) do not exclude negative values for the agglomeration bonus in some of their experiments, thus implicitly examining an agglomeration malus. We assume the farmers receive a payment per hectare of reserve but this payment is reduced when the remunerated parcel is adjacent to an existing reserve. We distinguish the parcels that are completely adjacent to the remunerated parcel from those having only one corner in common with this parcel. For example, if we assume a farmer receives a payment for the conversion of parcel 5 to the reserve (see Fig. 4.8). He will pay the total malus if parcel 2, 4, 6 or 8 is in the reserve. And he will pay a lower amount - say half the malus[12] - if parcel 1, 3, 7 or 9 is in the reserve, as these parcels only have one corner in common with parcel 5. The farmer pays the malus per adjacent parcel in reserve (or half the malus per parcel with one corner in common with the remunerated parcel). In the example below, where parcels in grey are in the reserve, the farmer has to pay 2.5 times the malus when receiving the payment for converting parcel 5 to the reserve.

We assume farmers can observe the existing parcels in reserve, as is consistent with reality. Moreover, we assume that when deciding which parcel to convert to reserve, they can communicate with their neighbors to coordinate in order to avoid an unexpected malus. In other words, farmers are aware of which parcels on neighbors' lands will be converted to reserve. This assumption is easily justified by the fact that, contrarily to the auction case where farmers are competitors (they have both conflicting and common interests, inducing a prisoners' dilemma), in the case of the agglomeration malus, farmers only have common interests to avoid the malus and obtain the greatest possible payment. Moreover, some experiments have demonstrated that, when it is in their interest, agents are able to coordinate facing an agglomeration payment (Parkhurst and Shogren, 2007).

We find that this instrument reaches 15% of reserve with a total public cost of ap-

[11] A real-world application of an agglomeration bonus is Oregon's Conservation Reserve Enhancement Program (CREP), established in 1998 with the goal of assisting the recovery of salmon and trout species through the creation of riparian buffers along stream habitat (Grout, 2009).

[12] Our spatial results are robust when changing this parameter from 1/2 to any $\alpha \in]0, 1[$. This is due to the fact that, in the framework of our model, there are no adjacent parcels in reserve at the equilibrium so any positive value yields the same spatial pattern.

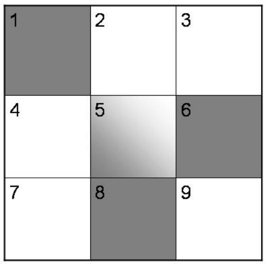


Fig. 4.8. The agglomeration malus

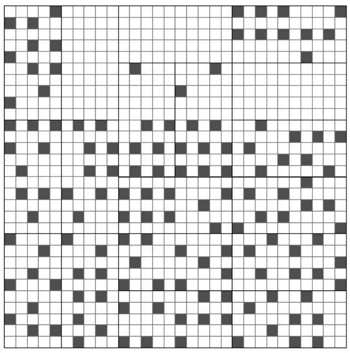


Fig. 4.9. Reserve location with the agglomeration malus

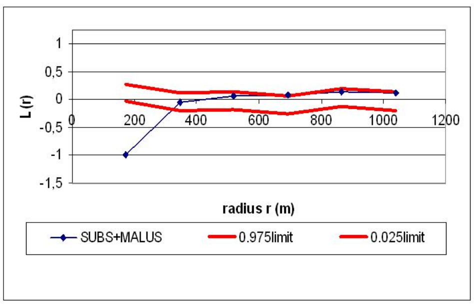


Fig. 4.10. The Ripley L function with the agglomeration malus

proximately **279 thousand euros**, which is the same amount as with the subsidy. This is not surprising given that, in our grid, farmers can locate the reserve patches so as not to pay the malus; they thus receive the same amount as with the standard subsidy. This instrument is therefore about twice more expensive than the auction scheme. However, it leads to the desired spatial pattern (see Fig. 4.9 and Fig. 4.10): the Ripley L function is inside the confidence envelop[13].

4.6 Summary and discussion

We have compared three incentive-based policy instruments - a subsidy per ha of reserve, an auction and an agglomeration malus - in order to reach a given size of reserve on agricultural lands, with reserve patches forming a random mosaic. In the framework of our model, the auction scheme has proven to be much more cost-efficient than the subsidy by reducing almost by half the public expenditures. The agglomeration malus is as costly as the subsidy and thus more costly than the auction but allows a better spatial pattern than both other instruments. As a result, we cannot rank the auction compared to the agglomeration malus as the former is more cost-efficient whereas the latter is more spatially efficient. We therefore have a trade-off between minimizing the public costs of the policy and reaching the desired spatial pattern of reserves.

Our work can be improved in many directions. The positive results on the auction's cost-efficiency must be mitigated for three main reasons. i) The specific characteristics of our case study leads to an insignificant margin in farmers' optimal bid, thus caricaturing the cost advantage of the auction. ii) The auction scheme may induce higher administrative costs than a standard subsidy due to a more complex procedure; data on the differences in administrative costs according to the instrument would be useful to incorporate this point in our analysis. iii) The fact that the auction is repeated may induce some strategic behavior and learning effects from the bidders, which could reduce the cost efficiency of this instrument.

Scope for further research includes introducing other policy instruments such as a heterogeneous payment scheme (based on mechanism design theory; see Wu and Babcock, 1996 and Glebe, 2008) or a reserve trading scheme, both potentially improving cost-efficiency. Also, we could improve the design of the auction scheme so as to deal more specifically with the spatial issue. This includes revising the scoring of bids taking

[13]Except for the first point (200 meters radius): 200 meters corresponds to the maximal distance between any adjacent plots. The malus therefore generates over-dispersion at this level.

into account a selection criteria which depends on the status of the adjacent parcel[14]. Furthermore, one of the priority extensions of our work would be to introduce a metric of the biological result per money spent, either by creating an indicator of the ecological result linked to the obtained spatial pattern (see Bretagnolle and Inchausti, 2005) or by coupling our economic model with an ecological model (see Barraquand and Martinet, 2011 for a first attempt with a theoretical model and see Drechsler et al., 2010).

[14]See Williams et al. (2012) for more on the scoring of bids and ecological metric.

Conclusion générale

Dans le cadre de cette thèse, nous nous sommes intéressés à la problématique générale de l'élaboration de politiques publiques permettant une répartition spatiale des activités agricoles efficace du point de vue environnemental, dans les domaines de la protection de la biodiversité et de la production de biomasse-énergie. Cette problématique concerne également d'autres sujets de recherche tels que la qualité de l'eau et la protection des aires de captages, que nous évoquions en introduction, mais aussi les différentes fonctions du paysage agricole comme la lutte contre l'érosion des sols. Les modèles, pour concevoir et évaluer de telles politiques, doivent être en mesure de rendre compte des changements d'activités et pratiques agricoles et de leur localisation. Cela nécessite de prendre en compte à la fois les aspects spatiaux, la prise de décision au niveau des exploitations agricoles et une modélisation fine des systèmes d'exploitation. Dans les articles qui constituent cette thèse, nous avons plus précisément abordé les aspects méthodologiques du développement de tels modèles.

Nous avons opté pour des modèles de programmation mathématique pour simuler les décisions des exploitations agricoles. Ils sont traditionnellement utilisés dans la conception et l'évaluation des politiques publiques dans le secteur agricole. Ils permettent de représenter explicitement les techniques de production -et donc le lien entre intrants, produits et impacts environnementaux-, d'introduire de nouvelles activités et pratiques, et d'évaluer le coût de mise en œuvre de politiques agro-environnementales par les exploitations. Nous avons intégré la dimension spatiale dans ces modèles, sous différentes formes qui sont : le contexte pédoclimatique, les distances et coûts de transport, les interactions entre plusieurs échelles spatiales, et les indicateurs de la configuration spatiale des activités.

Dans la première partie de la thèse, nous avons pris en compte le contexte pédoclimatique, les distances et les coûts de transport pour déterminer si la production de biomasse-énergie respecte les critères de durabilité sans intervention, ou s'il est nécessaire de mettre en œuvre une politique publique pour respecter ces critères.

Dans la deuxième partie de la thèse, nous avons tenu compte du contexte pédoclimatique, des interactions entre les échelles parcelles, exploitation et paysage, et d'un indicateur spatial, pour concevoir une politique agro-environnementale coût-efficace qui génère une configuration spatiale non-agrégée des parcelles contractualisées, adaptée à la conservation d'une espèce menacée.

Les principaux résultats des travaux conduits dans le cadre de cette thèse montrent l'importance de la prise en compte, dans les modèles de programmation mathématique, à la fois de la dimension spatiale et de la prise de décision au niveau des exploitations agricoles. La prise en compte simultanée de ces deux dimensions permet de mettre en évidence et d'étudier des arbitrages entre coûts et efficacité environnementale. Ainsi, cette approche permet d'éclairer la conception et l'évaluation des politiques agro-environnementales dans le secteur agricole.

La prise en compte simultanée des aspects spatiaux et de la prise de décision au niveau exploitation a permis d'une part d'évaluer finement les coûts et, d'autre part, de mettre en évidence et d'étudier des arbitrages entre coûts et efficacité environnementale des politiques publiques. Dans les chapitres 3 et 4, où les systèmes d'exploitation de type grandes cultures et élevage laitier mixte ont été représentés de manière détaillée, nous avons pu calculer le coût d'opportunité des parcelles en prairies gérées conformément au cahier des charges de la MAE "Outarde". Nous avons mis en évidence de grandes hétérogénéités d'une part en fonction de la qualité des sols et d'autre part entre les céréaliers et les éleveurs. Les éleveurs peuvent en effet procéder à un ajustement et une valorisation interne des productions via l'alimentation du troupeau, et donc diminuer leurs coûts d'opportunité. En intégrant la dimension spatiale du parcellaire, nous avons aussi évalué i) le coût d'obtention d'une surface suffisante de parcelles préservant l'habitat de l'Outarde selon la configuration spatiale requise, et ii) le coût de mise en conformité de chaque exploitation. Nous avons mis en évidence l'existence d'un arbitrage entre le coût et la configuration spatiale des parcelles "Outarde", à surface totale égale (cf chapitre 3). Nous avons ensuite comparé le coût budgétaire et l'efficacité de différents types d'instruments incitatifs sur notre zone d'étude stylisée : une subvention uniforme à paiement unique, une subvention uniforme associée à un malus à l'agglomération et un système d'enchère non spatialisée. Nous avons montré qu'une subvention uniforme n'était pas efficace d'un point de vue conservation (cf. chapitre 3) et qu'elle surcompensait les éleveurs. L'enchère permet de diminuer le coût de la mesure de presque 50% par rapport à la subvention, mais sans améliorer la configuration spatiale. Tandis que la subvention avec malus à l'agglomération est efficace et permet d'obtenir la bonne configuration, pour un coût budgétaire identique à la subvention (cf. chapitre 4).

Dans les chapitres 1 et 2, les décisions d'allocation des sols et de récolte du bois par les exploitants agricoles et forestiers ont été prises au niveau des cantons, chacun se comportant comme une exploitation. La prise en compte de l'hétérogénité des sols et de la compétition pour les terres entre cultures a permis i) de déterminer la quantité, le type et la localisation de la biomasse lignocellulosique produite pour un prix donné, à l'échelle de la région ; ii) de mettre en évidence l'importance de la compétition avec les cultures alimentaires dans le prix de la biomasse agricole ; et iii) de remettre en cause une idée communément admise et d'une nature à fausser les enjeux, à savoir : "si on laisse faire", les cultures énergétiques pérennes ne sont pas cultivées en premier lieu sur des terres marginales peu fertiles. Enfin la prise en compte de la compétition pour la biomasse forestière, entre les usages énergétiques et non énergétiques, a remis en cause une autre idée communément admise selon laquelle les rémanents, jusque là laissés au sol après récolte, constitueraient la principale source de biomasse forestière pour les usages énergétiques (cf. chapitre 1). Ils coûtent trop cher à récolter et la filière énergie se retrouve en compétition directe avec les autres usages du bois, ce qui est de nature à faire globalement augmenter les prix. On peut toutefois imaginer qu'il y aura, à terme, des innovations sur les procédés de récolte pour diminuer le coût global.

Dans le chapitre 1, la localisation d'une unité de bioénergie, comparée à une demande non spatialisée, a un impact sur le type de biomasse produite, sa localisation et sur le coût d'approvisionnement. Il existe un arbitrage entre le coût de la biomasse bord de champ et le coût de transport vers l'usine, dans les choix de production de la biomasse. Nous observons ainsi une concentration de la production. De plus, la pression environnementale (niveaux de fertilisation azotée minérale et de traitements phytosanitaires) peut augmenter localement suite aux changements d'usage des sols, directs et/ou indirects. Tous ces résultats sont confirmés dans le chapitre 2. Nous y abordons la viabilité de l'approvisionnement de l'unité de bioénergie au cours du temps, en fonction de sa stratégie d'approvisionnement, qui consiste à contractualiser une part plus ou moins élevée de sa demande avec des cultures pérennes et à compléter chaque année avec des cultures dédiées annuelles ou du bois. Il s'avère que la stratégie consistant à contractualiser tout l'approvisionnement avec une culture pérenne (Switchgrass) est la plus viable. Les résultats confirment aussi la compétition, potentiellement problématique, entre cultures alimentaires et énergétiques sur les terres les plus fertiles. Ceci risque d'engendrer une concurrence similaire à celle observée pour la production des biocarburants de 1ère génération, et de conduire au non respect des critères de durabilité de la Directive sur les énergies renouvelables (2009-28-CE). La production de biomasse-énergie est donc vraisemblablement sujette à un arbitrage entre la minimisation du coût d'approvisionnement en biomasse et des impacts environnementaux, qu'il conviendrait d'approfondir.

Les travaux présentés peuvent être améliorés de plusieurs façons.

Une des principales difficultés rencontrées lors du développement des modèles concerne la disponibilité de données techniques, économiques et administratives à un grain fin, cohérentes entre elles et éventuellement à plusieurs échelles. Ceci pose problème pour le calibrage ou la validation des modèles, qui se fait souvent à une échelle plus grossière (ex : département au lieu du canton). Quant au paramétrage des modèles, il repose souvent sur des dires d'experts pour les données technico-économiques sur les cultures par type de sol.

Les modèles présentés dans cette thèse sont basés sur la maximisation du profit par des agents économiques rationnels. Dans les travaux sur l'offre de biomasse énergie, il serait utile d'affiner la modélisation du comportement des exploitants. D'une part en intégrant des déterminants de l'adoption des cultures énergétiques pérennes, telles que le Miscanthus et le Switchgrass, qui sont sources de risques pour les exploitants (Bocquého, 2012). En effet, ce sont des productions nouvelles sur lesquelles on manque de connaissances et de références. Leur culture implique une immobilisation des parcelles sur plusieurs années, un gros investissement lors de l'implantation et des revenus différés, donc potentiellement des problèmes de trésorerie. D'autant plus que leurs débouchés sont encore peu développés, et qu'il existe une forte incertitude sur le prix de vente. D'autre part en intégrant des déterminants de la localisation des cultures pérennes au sein des exploitations (Martin et al., 2012). Il peut notamment s'agir de la distance et de l'accessibilité des parcelles par rapport au siège d'exploitation. On peut intégrer ces déterminants soit en les modélisant directement, par exemple en maximisant l'utilité espérée dans le cas du risque, soit en tirant de travaux existants des règles de décision à l'échelle de l'exploitation, qu'on introduit ensuite dans le modèle sous forme de contraintes par exemple.

Pour savoir s'il y a ou non besoin d'une politique publique pour mobiliser le potentiel de biomasse sans externalités environnementales négatives, à l'échelle d'une région, il faudrait affiner l'évaluation des impacts environnementaux. Les sorties du modèle, sur les niveaux d'intrants utilisés et les changements d'usage des sols, peuvent notamment être utilisées pour le calcul d'émissions de gaz à effet de serre ou pour des analyses de cycle de vie (Gabrielle, 2009). Il faudrait aussi affiner l'approche en ajoutant un niveau "parcelle", plus adapté à l'évaluation des impacts paysagers, ou travailler à un grain plus fin car la maille cantonale n'est pas adaptée aux plans d'approvisionnement pour les petites unités locales.

Enfin il existe des pistes pour aller plus loin dans la prise en compte de la spatialisation dans les modèles.

Tout d'abord, il serait intéressant de disposer d'un modèle qui puisse déterminer la configuration spatiale optimale des activités agricoles pour une politique environnementale donnée. Cela nécessiterait d'intégrer les indicateurs de configuration spatiale directement dans les modèles sous forme de contrainte. Il serait alors possible de minimiser les coûts pour un bénéfice environnemental donné, mais aussi de générer des frontières d'éco-efficacité en faisant varier la contrainte de coût. Les travaux que nous avons engagés sur ce point (cf. chapitre 3) doivent être poursuivis dans ce sens.

D'autre part, les impacts environnementaux s'expriment à différentes échelles. Par exemple, la production de biomasse-énergie a des impacts à la fois au niveau de la parcelle (ex : intensité d'utilisation des intrants), du paysage (création éventuelle d'une trame verte) et au niveau global (ex : émissions de gaz à effet de serre). De plus il existe des propriétés émergentes des processus physiques ou biologiques, qui ne se déduisent pas des niveaux inférieurs par simple agrégation. Pour simuler efficacement les effets des politiques environnementales et des choix des agriculteurs, il faut donc pouvoir rendre compte de la configuration spatiale des activités et pratiques agricoles à différentes échelles. Des travaux sont donc nécessaires pour développer des modèles i) qui prennent en compte le niveau des parcelles, ii) qui relient celles-ci à des exploitations agricoles car c'est à ce niveau que se prennent les décisions, et iii) qui aient un niveau d'agrégation suffisant pour évaluer les politiques publiques. Ce niveau variera, selon les problématiques, de la région, à la France entière, en passant par le bassin versant.

Bibliographie

ADEME, IFN, FCBA and SOLAGRO (2009). *Biomasse forestière, populicole et bocagère disponible pour l'énergie à l'horizon 2020*. Technical report, Etude réalisée pour le compte de l'ADEME , contrat n°0601C0134.

Agabriel, J., Champiaux, P. and Espinasse, C. (1999). Inration-prevalim 2.7 : logiciel de rationnement des ruminants. Dijon : INRAtion-CNERTA diffusion.

Ai, C., Chatrath, A. and Song, F. (2006). On the comovement of commodity prices. *American Journal of Agricultural Economics*, 88(3), 574–588.

Ando, A., Camm, J., Polasky, S. and Solow, A. (1998). Species distributions, land values, and efficient conservation. *Science*, 279(5359), 2126–2128.

Appelt, M. and Poethke, H. J. (1997). Metapopulation dynamics in a regional population of the blue-winged grasshopper (Oedipoda caerulescens ; Linnaeus, 1758). *Journal of Insect Conservation*, 1(4), 205–214.

ARVALIS (2007). *L6 Données technico-économiques des cultures alimentaires actuelles*. Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

ARVALIS/ONIDOL, G. (2009a). *L4 Données technico-économiques des cultures ligno-cellulosiques par canton et contexte pédo-climatique*. Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

ARVALIS/ONIDOL, G. (2009b). *L8-1 Estimation de la disposition à offrir des producteurs (paille et cultures énergétiques)*. Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

Aubin, J.-P. (1991). *Viability theory*. Birkhäuser.

Babcock, B., Marette, S. and Tréguer, D. (2011). Opportunity for profitable investments in cellulosic biofuels. *Energy Policy*, 39(2), 714–719.

Ballarin, A., Vecchiato, D., Tempesta, T., Marangon, F. and Troiano, S. (2011). Biomass energy production in agriculture : A weighted goal programming analysis. *Energy Policy*, 39(3), 1123–1131.

Bamière, L. (2013). A spatially explicit model to analyse the regional supply of lignocellulosic biomass, mimeo.

Bamière, L., Havlik, P., Jacquet, F., Lherm, M., Millet, G. and Bretagnolle, V. (2011). Farming system modelling for agri-environmental policy design : The case of a spatially non-aggregated allocation of conservation measures. *Ecological Economics*, 70(5), 891–899.

Bamière, L. et al. (2007). *L1 Typologie des cantons de la région-test.* Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

Barraquand, F. and Martinet, V. (2011). Biological conservation in dynamic agricultural landscapes : Effectiveness of public policies and trade-offs with agricultural production. *Ecological Economics*, 70(5), 910–920.

Beck, S. (2001). Autoregressive conditional heteroscedasticity in commodity spot prices. *Journal of Applied Econometrics*, 16(2), 115–132.

Berndes, G., Hoogwojk, M. and van den Broek, R. (2003). The contribution of biomass in the future global energy supply : A review of 17 studies. *Biomass and Bioenergy*, 25(1), 1–28.

Besag, J. (1977). Contribution to the discussion of dr ripley's paper. *Journal of the Royal Statistical Society*, B 39, 193–195.

Bocquého, G. (2012). *Risque, temps et adoption des cultures pérennes énergétiques : exemple du cas français.* Ph.D. thesis, AgroParisTech.

Bocquého, G. and Jacquet, F. (2010). The adoption of switchgrass and miscanthus by farmers : impacts of liquidity constraints and risk preferences. *Energy Policy*, 38(5), 2598–2607.

Bourgeois, C. (2012). *Régulation des pollutions azotées d'origine agricole.* Ph.D. thesis, AgroParisTech.

Bretagnolle, V. (2004). Prairies et cultures fourragères : Quels enjeux pour les oiseaux dans les milieux céréaliers intensifs ?

Bretagnolle, V. and Inchausti, P. (2005). Modelling population reinforcement at a large spatial scale as a conservation strategy for the declining little bustard (Tetrax tetrax) in agricultural habitats. *Animal Conservation*, 8, 59–68.

Bretagnolle, V., Villers, A., Denonfoux, L., Cornulier, T., Inchausti, P. and Badenhausser, I. (2011). Rapid recovery of a depleted population of little bustards tetrax tetrax following provision of alfalfa through an agri-environment scheme. *Ibis*, 153(1), 4–13.

Britz, W., Gocht, A., Pèrez Dominguez, T., I. abd Jansson, Grosche, S. and Zhao, N. (2012). Eu-wide (regional and farm level) effects of premium decoupling and harmonisation following the health check reform. *German Journal of Agricultural Economics*, 44–56.

Bryan, B. A., Ward, J. and Hobbs, T. (2008). An assessment of the economic and environmental potential of biomass production in an agricultural region. *Land Use Policy*, 25(4), 533–549.

Cason, T. N. and Gangadharan, L. (2004). Auction design for voluntary conservation programs. *American Journal of Agricultural Economics*, 86(5), 1211–1217.

Chamberlain, D. E., Fuller, R. J., Bunce, R. G. H., Duckworth, J. C. and Shrubb, M. (2000). Changes in the abundance of farmland birds in relation to the timing of agricultural intensification in England and Wales. *Journal of Applied Ecology*, 37(5), 771–788.

Chambers, R. G. (1992). On the design of agricultural policy mechanisms. *American Journal of Agricultural Economics*, 74(3), 646–654.

Dawson, P., Sanjuán, A. and White, B. (2006). Structural breaks and the relationship between barley and wheat futures prices on the London International Financial Futures Exchange. *Review of Agricultural Economics*, 28(4), 585–594.

De Lara, M. and Martinet, V. (2009). Multi-criteria dynamic decision under uncertainty : A stochastic viability analysis and an application to sustainable fishery management. *Mathematical Biosciences*, 217(2), 118–124.

Deaton, A. and Laroque, G. (1992). On the behaviour of commodity prices. *Review of Economic Studies*, 59(1), 1–23.

Diggle, P. (1983). Statistical analysis of spatial point patterns. Academic Press. London, UK.

Donald, P. F., Green, R. E. and Heath, M. F. (2001). Agricultural intensification and the collapse of Europe's farmland bird populations. *Proceedings of the Royal Society B-Biological Sciences*, 268(1462), 25–29.

Doyen, L. and De Lara, M. (2010). Stochastic viability and dynamic programming. *Systems and Control Letters*, 59(10), 629–634.

Drechsler, M., Wätzold, F., Johst, K., Bergmann, H. and Settele, J. (2007). A model-based approach for designing cost-effective compensation payments for conservation of endangered species in real landscapes. *Biological Conservation*, 140(1-2), 174–186.

Drechsler, M., Wätzold, F., Johst, K. and Shogren, J. F. (2010). An agglomeration payment for cost-effective biodiversity conservation in spatially structured landscapes. *Resource and Energy Economics*, 32(2), 261–275.

EEA (2006). *How much bioenergy can Europe produce without harming the environment ?* Report 7/2006, European Environment Agency.

Ekman, S. (2005). Cost-effective nitrogen leaching reduction as influenced by linkages between farm-level decisions. *Agricultural Economics*, 32(3), 297–309.

Ericsson, K. and Nilsson, L. (2006). Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass and Bioenergy*, 30(1), 1–15.

Falconer, K. (2000). Farm-level constraints on agri-environmental scheme participation : a transactional perspective. *Journal of Rural Studies*, 16(3), 379–394.

Falconer, K., Dupraz, P. and Whitby, M. (2001). An investigation of policy administrative costs using panel data for the English Environmentally Sensitive Areas. *Journal of Agricultural Economics*, 52(1), 83–103.

Falconer, K. and Hodge, I. (2001). Pesticide taxation and multi-objective policy-making : farm modelling to evaluate profit/environment trade-offs. *Ecological Economics*, 36(2), 263–279.

FCBA (2009). *L8-1 Estimation de la disposition à offrir des producteurs (bois et TCR).* Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

Ferraro, P. J. (2008). Asymmetric information and contract design for payments for environmental services. *Ecological Economics*, 65, 810–821.

Fischer, G., Prieler, S., van Velthuizen, H., Berndes, G., Faaij, A., Londo, M. and de Wit, M. (2010). Biofuel production potentials in europe : Sustainable use of cultivated land and pastures, part ii : Land use scenarios. *Biomass & Bioenergy*, 34(2), 173–187.

Flichman, G. and Jacquet, F. (2003). Le couplage des modèles agronomiques et économiques : intérêt pour l'analyse des politiques. *Cahiers d'Economie et Sociologie Rurales*, 67, 51–69.

Fudenberg, D. and Tirole, J. (1991). *Game Theory*. The MIT Press, Cambridge, Massachusetts.

Fujita, M., Krugman, P. and Venables, A. (2001). *The Spatial Economy : Cities, Regions, and International Trade*. MIT Press.

Gabrielle, B. (2009). *L7 Impacts environnementaux de la production des ressources lignocellulosiques*. Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

Galko, E. and Jayet, P. (2011). Economic and environmental effects of decoupled agricultural support in the eu. *Agricultural Economics*, 42(5), 605–618.

Getis, A. and Franklin, J. (1987). 2nd-order neighborhood analysis of mapped point patterns. *Ecology*, 68(3), 473–477.

Glebe, T. W. (2008). Scoring two-dimensional bids : how cost-effective are agri-environmental auctions ? *European Review of Agricultural Economics*, 35(2), 143–165.

Graham, R., English, B. and Noon, C. (2000). A Geographic Information System-based modelling system for evaluating the cost of delivered energy crop feedstock. *Biomass and Bioenergy*, 18(4), 309–329.

Gregory, R. D., van Strien, A., Vorisek, P., Meyling, A. W. G., Noble, D. G., Foppen, R. P. B. and Gibbons, D. W. (2005). Developing indicators for European birds. *Philosophical Transactions of the Royal Society B-Biological Sciences*, 360(1454), 269–288.

Grilli, E. and Yang, M. (1988). Primary commodity prices, manufactured goods prices, and the terms of trade of developing countries : What the long run shows. *World Bank Economic Review*, 2(1), 1–47.

Groth, M. (2005). Auctions in an outcome-based payment scheme to reward ecological services in agriculture - conception, implementation and results. In *45th Congress of Regional Sciences Association, Amsterdam, 23-27th August.*

Grout, C. A. (2009). Incentives for spatially coordinated land conservation : A conditional agglomeration bonus. *Michelle Haefele and Pete Morton The Influence of the Pace and Scale of Energy Development on Communities : Lessons from the Natural Gas Drilling Boom in the Rocky Mountains*, 8(2), 21.

Guindé, L., Jacquet, F. and Millet, G. (2008). Impacts du développement des biocarburants sur la production française de grandes cultures. *Review of Agricultural and Environmental Studies*, 89(4), 55–81.

Haase, P. (1995). Spatial pattern-analysis in ecology based on ripley k-function - Introduction and methods of edge correction. *Journal of Vegetation Science*, 6(4), 575–582.

Hamaide, B. and Sheerin, J. (2011). Species protection from current reserves : Economic and biological considerations, spatial issues and policy evaluation. *Ecological Economics*, 70(4), 667–675.

Hanski, I. (1999). *Metapopulation ecology*. Oxford University Press.

Hartig, F. and Drechsler, M. (2009). Smart spatial incentives for market-based conservation. *Biological Conservation*, 142(4), 779–788, hartig, Florian Drechsler, Martin.

Havlik, P., Veysset, P., Boisson, J. M., Lherm, M. and Jacquet, F. (2005). Joint production under uncertainty and multifunctionality of agriculture : policy considerations and applied analysis. *European Review of Agricultural Economics*, 32(4), 489–515.

Helfand, G. E., Berck, P. a. and Maull, T. (2003). *Handbook of Environmental Economics*, volume 1, chapter The theory of pollution policy. Amsterdam, The Netherlands : Elsevier, (pp. 249–303).

Hellmann, F. and Verburg, P. (2011). Spatially explicit modelling of biofuel crops in Europe. *Biomass and Bioenergy*, 35(6), 2411–2424.

van der Hilst, F., Dornburg, V., Sanders, J. P. M., Elbersen, B., Graves, A., Turkenburg, W. C., Elbersen, H. W., van Dam, J. M. C. and Faaij, A. P. C. (2010). Potential, spatial distribution and economic performance of regional biomass chains : The north of the netherlands as example. *Agricultural Systems*, 103(7), 403–417.

Hynes, S., Farrelly, N., Murphy, E. and O'Donoghue, C. (2008). Modelling habitat conservation and participation in agri-environmental schemes : A spatial microsimulation approach. *Ecological Economics*, 66(2-3), 258–269.

In, F. and Inder, B. (1997). Long-run relationships between world vegetable oil prices. *The Australian Journal of Agricultural and Resource Economics*, 41(4), 455–470.

Inchausti, P. and Bretagnolle, V. (2005). Predicting short-term extinction risk for the declining Little Bustard (Tetrax tetrax) in intensive agricultural habitats. *Biological Conservation*, 122(3), 375–384.

Jacquet, F., Butault, J. P. and Guichard, L. (2011). An economic analysis of the possibility of reducing pesticides in french field crops. *Ecological Economics*, 70(9), 1638–1648.

Jiguet, F. (2002). Arthropods in diet of Little Bustards Tetrax tetrax during the breeding season in western France. *Bird Study*, 49, 105–109.

Jiguet, F., Arroyo, B. and Bretagnolle, V. (2000). Lek mating systems : a case study in the Little Bustard Tetrax tetrax. *Behavioural Processes*, 51(1-3), 63–82.

Johst, K., Drechsler, M. and Watzold, F. (2002). An ecological-economic modelling procedure to design compensation payments for the efficient spatio-temporal allocation of species protection measures. *Ecological Economics*, 41(1), 37–49.

Jolivet, C. and Bretagnolle, V. (2002). L'outarde canepetière en france : évolution récente des populations, bilan des mesures de sauvegarde et perspectives d'avenir. *Alauda*, 70, 93–96.

Kirkpatrick, J. B. (1983). An iterative method for establishing priorities for the selection of nature reserves - an example from Tasmania. *Biological Conservation*, 25(2), 127–134.

Kirwan, B., Lubowski, R. N. and Roberts, M. J. (2005). How cost-effective are land retirement auctions ? estimating the difference between payments and willingness to accept in the conservation reserve program. *American Journal of Agricultural Economics*, 87(5), 1239–1247.

Klemperer, P. (1999). Auction theory : A guide to the literature. *Journal of economic surveys*, 13(3), 227–286.

Kocoloski, M., Griffin, M. and Matthews, S. (2011). Impacts of facility size and location decisions on ethanol production cost. *Energy Policy*, 39(1), 47–56.

Kuhfuss, L., Jacquet, F., Preget, R. and Thoyer, S. (2012). Le dispositif des maet pour l'enjeu eau : Une fausse bonne idée ? *Review of Agricultural and Environmental Studies*, 93(4).

Latacz-Lohmann, U. and Van der Hamsvoort, C. (1997). Auctioning conservation contracts : a theoretical analysis and an application. *American Journal of Agricultural Economics*, 79(2), 407–418.

Latacz-Lohmann, U. and Van der Hamsvoort, C. (1998). Auctions as a means of creating a market for public goods from agriculture. *Journal of Agricultural Economics*, 49(3), 334–345.

Latacz-Lohmann, U. and Schilizzi, S. (2005). *Auctions for conservation constracts : a review of the theoretical and emprirical literature*. Technical report, Report to the Scottish Executive Environment and Rural Affairs Department.

Le Roux, X., Barbault, R., Baudry, J., Burel, F., Doussan, I., Garnier, E., Herzog, F., Lavorel, S., Lifran, R., Roger-Estrade, J., Sarthou, J. and Trommetter, M. (2008). *Agriculture et biodiversité. Valoriser les synergies.* Technical report, Expertise scientifique collective, rapport, INRA (France).

Leduc, S., Schmid, E., Obersteiner, M. and Riahi, K. (2009). Methanol production by gasification using a geographically explicit model. *Biomass & Bioenergy*, 33(5), 745–751.

Lensink, S. and Londo, M. (2010). Assessment of biofuels supporting policies using the biotrans model. *Biomass and Bioenergy*, 34(2), 218–226.

Lewis, D. J. and Plantinga, A. J. (2007). Policies for habitat fragmentation : Combining econometrics with GIS-based landscape simulations. *Land Economics*, 83(2), 109–127.

Lewis, D. J., Plantinga, A. J., Nelson, E. and Polasky, S. (2011). The efficiency of voluntary incentive policies for preventing biodiversity loss. *Resource and Energy Economics*, 33(1), 192–211.

Lewis, D. J., Plantinga, A. J. and Wu, J. J. (2009). Targeting Incentives to Reduce Habitat Fragmentation. *American Journal of Agricultural Economics*, 91(4), 1080–1096.

Londo, M., Lensink, S., Wakker, A., Fischer, G., Prieler, S., van Velthuizen, H., de Wit, M., Faaij, A., Junginger, M., Berndes, G., Hansson, J., Egeskog, A., Duer, H., Lundbaek, J., Wisniewski, G., Kupczyk, A. and Konighofer, K. (2010). The refuel eu road map for biofuels in transport : Application of the project's tools to some short-term policy issues. *Biomass & Bioenergy*, 34(2), 244–250.

Louhichi, K. and Valin, H. (2012). Impact of eu biofuel policies on the french arable sector : A micro-level analysis using global market and farm-based supply models. *Review of Agricultural and Environmental Studies*, 93(3).

Martin, L., Wohlfahrt, J., Le Ber, F. and Benoît, M. (2012). L'insertion territoriale des cultures biomasses pérennes. etude de cas sur le miscanthus en côte d'or (bourgogne, france). *L'Espace Géographique*, 41(2), 138–153.

McAfee, R. P. and McMillan, J. (1987). Auctions and bidding. *Journal of Economic Literature*, 25(2), 699–738.

Milgrom, P. (1987). Auction theory. *Advances in Economic Theory*, 1–32.

Mouysset, L., Doyen, L., Jiguet, F., Allaire, G. and Leger, F. (2011). Bio economic modeling for a sustainable management of biodiversity in agricultural lands. *Ecological Economics*, 70(4), 617–626.

Naidoo, R., Balmford, A., Ferraro, P. J., Polasky, S., Ricketts, T. H. and Rouget, M. (2006). Integrating economic costs into conservation planning. *Trends in Ecology & Evolution*, 21(12), 681–687.

Nalle, D. J., Montgomery, C. A., Arthur, J. L., Polasky, S. and Schumaker, N. H. (2004). Modeling joint production of wildlife and timber. *Journal of Environmental Economics and Management*, (48), 997–1017.

Pain, D. and Dixon, J. (1997). Why farming birds in Europe ? In *Farming birds in Europe*, (pp. 1–24). London : Academic Press.

Parkhurst, G. M. and Shogren, J. F. (2007). Spatial incentives to coordinate contiguous habitat. *Ecological Economics*, 64(2), 344–355.

Parkhurst, G. M. and Shogren, J. F. (2008). Smart subsidies for conservation. *American Journal of Agricultural Economics*, 90(5), 1192–1200.

Parkhurst, G. M., Shogren, J. F., Bastian, C., Kivi, P., Donner, J. and Smith, R. B. (2002). Agglomeration bonus : an incentive mechanism to reunite fragmented habitat for biodiversity conservation. *Ecological economics*, 41(2), 305–328.

Peerlings, J. and Polman, N. (2004). Wildlife and landscape services production in Dutch dairy farming ; jointness and transaction costs. *European Review of Agricultural Economics*, 31(4), 427–449.

Peerlings, J. and Polman, N. (2008). Agri-environmental contracting of Dutch dairy farms : the role of manure policies and the occurrence of lock-in. *European Review of Agricultural Economics*, 35(2), 167–191.

Petersen, J. (2008). Energy production with agricultural biomass : environmental implications and analytical challenges. *European Review of Agricultural Economics*, 35(3), 385–408.

Pfaffenzeller, S., Newbold, P. and Rayner, A. (2007). A short note on updating the Grilli and Yang commodity price index. *World Bank Economic Review*, 21(1), 151–163.

Pindyck, R. and Rotemberg, J. (1990). The excess co-movement of commodity prices. *Economic Journal*, 100(403), 1173–1189.

Polasky, S., Camm, J. D. and Garber-Yonts, B. (2001). Selecting biological reserves cost-effectively : An application to terrestrial vertebrate conservation in Oregon. *Land Economics*, 77(1), 68–78.

Polasky, S., Nelson, E., Camm, J., Csuti, B., Fackler, P., Lonsdorf, E., Montgomery, C., White, D., Arthur, J., Garber-Yonts, B., Haight, R., Kagan, J., Starfield, A. and Tobalske, C. (2008). Where to put things ? spatial land management to sustain biodiversity and economic returns. *Biological Conservation*, 141(6), 1505 – 1524.

Polasky, S., Nelson, E., Lonsdorf, E., Fackler, P. and Starfield, A. (2005). Conserving species in a working landscape : Land use with biological and economic objectives. *Ecological Applications*, 15(4), 1387–1401.

Reeson, A. F., Rodriguez, L. C., Whitten, S. M., Williams, K., Nolles, K., Windle, J. and Rolfe, J. (2011). Adapting auctions for the provision of ecosystem services at the landscape scale. *Ecological Economics*, 70(9), 1621–1627.

Ripley, B. D. (1977). Modeling spatial patterns. *Journal of the Royal Statistical Society Series B-Methodological*, 39(2), 172–212.

Ripley, B. D. (1981). *Spatial Statistics*. New York, NY : Wiley-Interscience.

Rousseau, S. and Moons, E. (2006). Auctioning conservation contracts : An application to the flemish afforestation policy. *Available at SSRN 1114025*.

Rozakis, S. and Sourie, J.-C. (2005). Micro-economic modelling of biofuel system in France to determine tax exemption policy under uncertainty. *Energy Policy*, 33(2), 171–182.

Saïd, S. and Thoyer, S. (2007). *Agri-environmental auctions with synergies.* Working Papers 07-07, LAMETA, Universtiy of Montpellier.

Salamolard, M. and Moreau, C. (1999). Habitat selection by Little Bustard Tetrax tetrax in a cultivated area of France. *Bird Study*, 46, 25–33.

Scarlat, N. and Dallemand, J.-F. (2011). Recent developments of biofuels/bioenergy sustainability certification : A global review. *Energy Policy*, 39(3), 1630–1646.

Schilizzi, S. and Latacz-Lohmann, U. (2007). Assessing the performance of conservation auctions : an experimental study. *Land Economics*, 83(4), 497–515.

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G. and Schmid, E. (2010). Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass : A spatially explicit comparison of conversion technologies. *Applied Energy*, 87(7), 2128–2141.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu, T.-H. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319(5867), 1238–1240.

Smith, R. B. and Shogren, J. F. (2002). Voluntary incentive design for endangered species protection. *Journal of Environmental Economics and Management*, 43(2), 169–187.

Soule, M. E. and Simberloff, D. (1986). What do genetics and ecology tell us about the design of nature-reserves. *Biological Conservation*, 35(1), 19–40.

Sourie, J., Tréguer, D. and Rozakis, S. (2005). *L'ambivalence des filières biocarburants.* Technical Report 2, INRA Sciences Sociales.

Stoneham, G., Chaudhri, V., Ha, A. and Strappazzon, L. (2003). Auctions for conservation contracts : an empirical examination of Victoria's BushTender trial. *Australian Journal of Agricultural and Resource Economics*, 47(4), 477–500.

Taylor, M. A., Sohngen, B., Randall, A. and Pushkarskaya, H. (2004). Group contracts for voluntary nonpoint source pollution reductions : evidence from experimental auctions. *American Journal of Agricultural Economics*, 86(5), 1196–1202.

Thisse, J. F. (1997). L'oubli de l'espace dans la pensée économique. *Revue Région et Développement*, 6, 13–39.

Tittmann, P. W., Parker, N. C., Hart, Q. J. and Jenkins, B. M. (2010). A spatially explicit techno-economic model of bioenergy and biofuels production in california. *Journal of Transport Geography*, 18(6), 715–728.

Ugarte, D. G. D. and Ray, D. E. (2000). Biomass and bioenergy applications of the polysys modeling framework. *Biomass & Bioenergy*, 18(4), 291–308.

Vanewright, R. I., Humphries, C. J. and Williams, P. H. (1991). What to protect - systematics and the agony of choice. *Biological Conservation*, 55(3), 235–254.

Veysset, P., Bebin, D. and Lherm, M. (2005). Adaptation to Agenda 2000 (CAP reform) and optimisation of the farming system of French suckler cattle farms in the Charolais area : a model-based study. *Agricultural Systems*, 83(2), 179–202.

Wätzold, F. and Drechsler, M. (2005). Spatially uniform versus spatially heterogeneous compensation payments for biodiversity-enhancing land-use measures. *Environmental & Resource Economics*, 31(1), 73–93.

Wätzold, F., Lienhoop, N., Drechsler, M. and Settele, J. (2008). Estimating optimal conservation in the context of agri-environmental schemes. *Ecological Economics*, 68(1-2), 295–305.

van Wenum, J. H., Wossink, G. A. A. and Renkema, J. A. (2004). Location-specific modeling for optimizing wildlife management on crop farms. *Ecological Economics*, 48(4), 395–407.

Williams, J., ReVelle, C. and Levin, S. (2005). Spatial attributes and reserve design models : A review. *Environmental Modeling & Assessment*, 10(3), 163–181.

Williams, K. J., Reeson, A. F., Drielsma, M. J. and Love, J. (2012). Optimised whole-landscape ecological metrics for effective delivery of connectivity-focused conservation incentive payments. *Ecological Economics*, 81, 48–59.

de Wit, M. and Faaij, A. (2010). European biomass resource potential and costs. *Biomass & Bioenergy*, 34(2), 188–202.

Wolff, A., Dieuleveut, T., Martin, J. L. and Bretagnolle, V. (2002). Landscape context and little bustard abundance in a fragmented steppe : implications for reserve management in mosaic landscapes. *Biological Conservation*, 107(2), 211–220.

Wolff, A., Paul, J.-P., Martin, J.-L. and Bretagnolle, V. (2001). The benefits of extensive agriculture to birds : the case of the little bustard. *Journal of Applied Ecology*, 38(5), 963–975.

Wossink, A., van Wenum, J., Jurgens, C. and de Snoo, G. (1999). Co-ordinating economic, behavioural and spatial aspects of wildlife preservation in agriculture. *European Review of Agricultural Economics*, 26(4), 443–60.

Wossink, G. A. A., de Koeijer, T. J. and Renkema, J. A. (1992). Environmental-economic policy assessment : A farm economic approach. *Agricultural Systems*, 39(4), 421–438.

Wu, J. and Babcock, B. (2001). Spatial heterogeneity and the choice of instruments to control nonpoint pollution. *Environmental and Resource Economics*, 18, 173–192.

Wu, J. J. and Babcock, B. A. (1996). Contract design for the purchase of environmental goods from agriculture. *American Journal of Agricultural Economics*, 78(4), 935–945.

Zilberman, D., Hochman, G., Rajagopal, D., Sexton, S. and Timilsina, G. (2013). The impact of biofuels on commodity food prices : Assessment of findings. *American Journal of Agricultural Economics*, 95(2), 275–281.

Résumé

Dans le cadre de cette thèse, nous nous sommes intéressés à la problématique générale de l'élaboration de politiques publiques permettant une répartition spatiale des activités agricoles efficace du point de vue environnemental, dans les domaines de la protection de la biodiversité et de la production de biomasse-énergie. Les modèles que nous avons construits pour concevoir et évaluer de telles politiques permettent de rendre compte des changements d'activités et pratiques agricoles et de leur localisation. Cela nécessite de prendre en compte à la fois les aspects spatiaux, la prise de décision au niveau des exploitations agricoles et une modélisation fine des systèmes d'exploitation.

Dans la première partie de la thèse, nous nous plaçons en amont de la conception d'une politique publique et nous essayons de déterminer si la production de biomasse-énergie peut se faire de manière durable sans intervention, ou s'il est nécessaire de mettre en oeuvre une politique publique pour respecter les critères de durabilité. Nous développons un modèle régional d'offre de biomasse agricole et forestière, spatialement explicite et à maille cantonale. Les aspects spatiaux y sont abordés à la fois par la prise en compte du contexte agro-pédo-climatique et des distances et coûts de transport entre les lieux de production et d'utilisation de la biomasse. Nous appliquons le modèle à la région Champagne-Ardenne pour analyser l'offre de biomasse et les impacts de sa production, face à une demande accrue. Les résultats mettent en évidence la compétition, potentiellement problématique, entre cultures alimentaires et énergétiques sur les terres les plus fertiles. Ceci risque d'engendrer une concurrence similaire à celle observée pour la production des biocarburants de 1ère génération, et de conduire au non respect des critères de durabilité de la Directive sur les énergies renouvelables (2009-28-CE).

Dans la deuxième partie de la thèse, nous nous penchons sur la conception d'une politique agro-environnementale coût-efficace, qui génère une configuration spatiale non-agrégée des parcelles contractualisées, adaptée à la conservation de l'Outarde Canepetière dans la Plaine de Niort. Nous développons un modèle associant une représentation fine des systèmes d'exploitation à une approche spatialement explicite, basée sur la prise en compte du contexte agro-pédo-climatique, des interactions entre les échelles parcelles, exploitation et paysage, ainsi que sur le calcul d'un indicateur spatial. Nous comparons, entre autres, le coût budgétaire et l'efficacité de différents instruments incitatifs. Nous montrons i) qu'une subvention uniforme n'est pas efficace d'un point de vue conservation ; ii) qu'une enchère permet de diminuer le coût de la mesure de 50% par rapport à la subvention, mais sans améliorer la configuration spatiale ; iii) tandis qu'une subvention couplée à un malus à l'agglomération est efficace en terme de configuration spatiale, pour un coût équivalent à celui de la subvention uniforme.

La prise en compte simultanée, dans les modèles de programmation mathématique, de la dimension spatiale et de la prise de décision au niveau des exploitations agricoles permet d'une part d'évaluer finement les coûts et, d'autre part, de mettre en évidence et d'étudier des arbitrages entre coûts et efficacité environnementale des politiques publiques. Ainsi, cette approche permet d'éclairer la conception et l'évaluation des politiques environnementales dans le secteur agricole.

Abstract

This thesis tackles the difficulty of designing public policies that allow for an effective spatial distribution of agricultural activities from an environmental point of view, in the fields of the production of biomass for energy purposes and the conservation of biodiversity. The models developed herein to design and assess such policies account for changes in agricultural activities and practices as well as their location. This achieved by considering spatial features, decision making at the farm level, and detailed modelling of farming systems.

In the first part, we place ourselves upstream from policy design so as to determine if lignocellulosic biomass production complies with sustainability criteria or if there is a need to implement a policy to do so. We have developed a spatially-explicit regional supply model with a county sub-level for agricultural and forest lignocellulosic biomass. Spatial aspects are accounted for in terms of agropedoclimatic context as well as transportation distances and costs from counties to bioenergy facilities. We have applied this modelling approach to the case of the French Champagne-Ardenne region, to analyse biomass supply and its impacts when facing an increased demand for lignocellulosic feedstock. Our results highlight the potentially problematic competition for the most fertile agricultural land between food and energy crops. This could lead to both land-use competition issues similar to those observed for the production of first generation biofuels and non-compliance to the sustainability criteria laid out in the EU Directive on Renewable Energy Sources (2009-28-CE).

In the second part, we address the issue of designing a cost-effective agro-environmental policy which generates a non-agregated spatial distribution of fields enrolled in a programme aimed at Tetrax tetrax conservation in the Plaine de Niort, France. We have developed a spatially explicit and detailed farm-based optimization model that accounts for the agropedoclimatic context as well as the relationships between the field, farm and landscape levels. Moreover the model is coupled with a relevant spatial pattern index. We compare the budgetary cost and effectiveness of different policy instruments. Our results show that i) a uniform subsidy is not effective; ii) an auction scheme reduces public expenditures almost by half, but without improving the spatial pattern; while iii) an agglomeration malus is effective in terms of spatial pattern, for a cost equivalent to the cost of the uniform subsidy.

Treating both the spatial aspects and decision-making at the farm level in mathematical programming models makes it possible, on the one hand, to more accurately assess compliance costs and, on the other hand, to highlight and analyse the tradeoffs between the cost and the environmental effectiveness of public policies. This modelling approach therefore provides the means to better design and assess environmental policies in the agricultural sector.