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Are soil sealing indicators sufficient to guide urban planning? Insights from an ecosystem services assessment in the Paris metropolitan area

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Abstract

Urban sprawl impacts are critical in the evaluation of planning decisions and often monitored by indicators of soil sealing. In France, these indicators are required by law to be reported in environmental assessments of planning documents. Although monitoring of soil sealing is important to limit environmental impacts, focusing on this sole dimension in urban planning can be reductive. In this paper, we explore to what extent ecosystem services (ES) indicators, measuring the benefits to humans provided by healthy ecosystems, are captured by soil sealing indicators by comparing their temporal and spatial evolutions. Through consulting with urban planning stakeholders, we model and map the spatial and temporal evolutions over a 35 year period of soil sealing and eight priority ES in the Paris metropolitan area (agricultural potential, groundwater recharge, global climate regulation, water quality regulation through nutrient retention, urban heat mitigation, flood mitigation, recreational potential and natural heritage). We highlight the spatial and temporal matches and mismatches between the two types of indicators (ES and soil sealing) and demonstrate that a large part of ES variations are not well captured by soil sealing indicators in time and space (spatial match with the eight ES is only found for 10% of the Paris metropolitan area). This calls for finer, ES-based, diagnosis in land use planning that could usefully illuminate the gains and losses related to land use and land management policies by taking into account the environmental and societal impacts of urban sprawl.

1. Introduction

About 290 000 km^2 of natural and semi-natural habitats are forecast to be converted to urban land uses by 2030 (McDonald *et al* 2020). Such projections pose important issues in terms of biodiversity (Güneralp and Seto 2013, Ceballos *et al* 2015) and human wellbeing (IPBES 2018, Ipbes *et al* 2019). To cope with these challenges, the evaluation of urban sprawl impacts became an important component of the urban political agenda, often materialized by monitoring indicators of land take or soil sealing[6]. In Europe for instance, such indicators have been developed by the Environmental European Agency[7]

6 Soil sealing is a polysemic term. In this paper, following Prokop *et al* (2011), we define soil sealing as the permanent covering of soil by completely or partly impermeable artificial material. 'Land take' and 'urbanization' are related terms, with land take often including urban green areas as well, and urbanization refer to the process underlying soil sealing (Marquard *et al* 2020).

7 www.eea.europa.eu/data-and-maps/indicators/land-take-3/assessment.

to improve environmental monitoring and support environmental policy making. Globally, Sustainable Development Goal 11 from the United Nations uses land consumption to track progress on sustainable urbanisation (Marquard *et al* 2020). Similar indicators are also used at city or national scales, such as in Hong Kong, Vancouver or Melbourne (Bibri *et al* 2020, Nadeem *et al* 2021), or Germany, Austria, or France (Decoville 2018). In France, soil sealing rates became one of the indicators tracking national losses of wealth[8]. At the local level, planning documents are required by law to report soil sealing evolutions in their environmental assessments with quantitative indicators such as the share of highly sealed surfaces per geographical entity (SCoT and PLU[9] since the Grenelle II Law in 2010, the SRADDET and SDRIF since the NOTRe law of 2015).

Although soil sealing monitoring is important to limit environmental impacts, using this sole dimension to assess environmental impacts in urban planning can be reductive, limiting planning evaluation to two alternatives for soils: 'artificial' and 'natural/semi-natural'. This vision raises at least three environmental and social issues for decision making. First, the potential cumulative effect of soil sealing combined with other sources of land degradation is disregarded, as soil sealing evaluation may overlook land degradation due to other drivers such as agricultural or forestry practices (Wilkinson *et al* 2013, Tardieu *et al* 2015, Woodruff and BenDor 2016). Second, this vision lacks a strategic spatial overview considering that any soil sealing is equivalent, irrespective of its location and individuals potentially affected by the environmental change (Artmann *et al* 2014). Third, this type of indicator does not provide information with stakeholders or citizens on the evolution of the ecological functions on which societies depend for their quality of life, well-being and health. In this context, calls for broadening the monitoring of ecosystems health and outputs for human well-being in urban planning have emerged, suggesting to complement soil sealing analyses by, for example, ecosystem services (ES) indicators (Euliss *et al* 2010, Cortinovis and Geneletti 2018). ES have the advantages of representing a wide range of ecological production functions of importance to multiple beneficiaries, and may thus refine the information on trade-offs involved by planning decisions in order to better target sustainable urban patterns. Moreover, it allows adopting a less binary vision between 'artificial' and 'natural' land uses, by considering a whole continuity between the two and taking into account many different land uses that are intermediate (e.g. diffuse housing).

Despite increasing evidence that the improvement of ES increases the quality of life in cities[10] (Díaz *et al* 2018, Keeler *et al* 2019), the recent special IPCC (2019) deplored that 'currently, maintenance/improvement of ecosystem services are rarely considered in urban planning processes' (p 186). Multiple case studies worldwide acknowledged this gap and demonstrated that the explicit mention of ES remains anecdotal in the majority of urban planning documents (e.g. Colding 2011, Wilkinson *et al* 2013, Albert *et al* 2014, Mascarenhas *et al* 2014, McPhearson *et al* 2015, Cabral *et al* 2016, Woodruff and BenDor 2016, Grêt-Regamey *et al* 2017, Frantzeskaki *et al* 2019). Their implicit reference is nevertheless increasingly observed in planning documents (Hansen *et al* 2015), even though the growing level of awareness is not necessarily accompanied by a high level of implementation (Posner *et al* 2016). The Paris metropolitan area is no exception, as ES are neither mentioned nor quantified in major strategic urban plans, including in the Regional Master Plan shaping the overall future planning of the area[11].

In this paper, we explore to what extent ES temporal and spatial evolutions are captured by soil sealing indicators required in urban planning documents. To do so, we model and map the spatial and temporal evolutions of eight priority ES in the Paris metropolitan area over a 35 year period, and compare results to soil sealing evolutions. Spatial and temporal matches between soil sealing and ES are evaluated by assuming that, in time and space, a positive trend of net soil sealing would negatively impact the ES supply trend, or that greening trends would impact positively ES trends. Otherwise, a mismatch is considered, representing a more complex spatial or structural relationship between ES evolutions and soil sealing.

2. Material and methods

2.1. Case study: Paris metropolitan area (Ile-de-France region)

In proportion to its population, France is the most artificialized country in Europe (47 km^2 of artificial surfaces per 100 000 inhabitants compared to 41 in Germany, 30 in the United Kingdom and Spain,

[8] www.insee.fr/fr/statistiques/3303511?sommaire=3353488.

[9] The SRADDET (Master plan for the region) the SCOT (Territorial Coherence Scheme) and the PLU (Local urban plan) are respectively the French regional, territorial and municipal plans. The SRADDET (SDRIF for Ile-de-France) and SCoTs must ensure a balance between urban renewal, controlled urban development and the preservation of natural areas and landscapes.

[10] Since the contribution of Bolund and Hunhammar (1999), numerous articles have shown the important contribution of nature in cities in regulating heat islands (Stewart and Oke 2012), regulating air quality, protecting against flooding, and providing recreational opportunities with positive impacts on the health of urban dwellers (Keeler *et al* 2019).

[11] Refer to SI section 2 (available online at stacks.iop.org/ERL/16/104019/mmedia) for further detail in the urban planning governance in France and current uptake of ES.

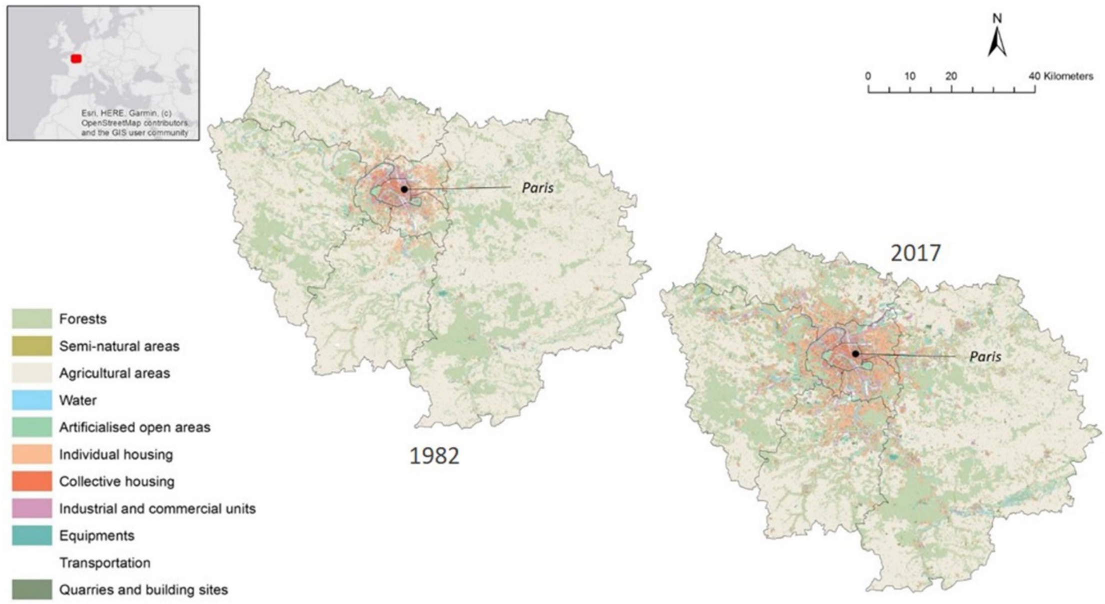

Figure 1. Land use and cover in the Paris metropolitan area (Ile-de-France region) in 1982 and 2017, France (based on land cover mode (LCM)[12], developed by the Institut Paris Region)[13]. Reprinted from Liotta *et al* (2020), Copyright (2020), with permission from Elsevier.

and 26 in Italy, France Stratégie, 2019). Soil sealing in France is about 260 km^2 yr^{-1} and sealed surface occupy 9.4% of the French territory (Béchet *et al* 2017). With a surface area of 12 012 km^2 (2% of the national territory), Île-de-France is one of the smallest French region, but the most densely populated (in 2019, nearly 20% of the population of mainland France, INSEE). This region roughly corresponds to the metropolitan area of Paris[14], and comprises eight departments: the actual city of Paris, which is only a small part of the region, the 'little crown' (inner suburb), and the 'big crown' (outer suburb)[15]. The region is predominantly agricultural (50%) dominated by field crops (wheat, barley, rape, beet representing 90% of the agricultural surface), then forestry (24%), and the rest is being occupied by artificial areas (22.5%), water surfaces and semi-natural areas (figure 1). Sealed surfaces occupy a large part of the inner suburbs of Paris, containing individual housing and facilities (health, sports, education and administration). The inner city of Paris is mainly occupied by collective housing, artificial open spaces and transport infrastructures.

Urban planning in Ile-de-France is framed by the Regional Master Plan (SDRIF 2013), consulted by all land planning stakeholders, containing regulatory orientations for the region (by 2030 for the last master plan voted in 2013). Every planning document defined at a lower level (PLU, SCoTs) has, by law, to comply with the prescriptions defined by the master plan[16] and especially with the 'map of general end-use of different parts of the territory'. This map targets and locate the future development of the region in terms of transport infrastructure, areas to densify, housing to develop, and green spaces to build. The planning document is subject to environmental impact assessment and must produce quantitative environmental indicators described in table 1.

2.2. Calculation of net soil sealing and ES

We involved 56 stakeholders from the urban planning, environmental protection, NGOs and civil society sectors, representing more than 27 French and European institutions (appendix A) to co-define soil

[12] The LCM (MOS in French) is a digital inventory of land use and land cover in the Île-de-France region provided by the Paris Region Institute. It has been updated regularly since its 1st edition in 1982 and is updated approximately every 5 years. We used the LCM for the years 1982, 1987, 1990, 1994, 1999, 2003, 2008, 2012, 2017. The LCM is based on aerial photos covering the entire regional territory, and distinguishes agricultural, natural, forest and urban areas (housing, infrastructure, equipment, economic activities, etc) according to a classification of up to 81 legend items (see SI section 1) with a 25 m resolution.

[13] The interactive map of differences in Land use and Land cover between 1982 and 2017 can be found here.

[14] www.insee.fr/fr/information/4808607.

[15] Inner suburb comprises the three closest departments from Paris, i.e. Seine-Saint-Denis, Hauts-de-Seine and Val-de-Marne and outer suburbs the four farthest departments, i.e. Seine-et-Marne, Val-d'Oise, Essonne and Yvelines.

[16] Legal links are described in the SI document-section 1.2.

Table 1. Current (mandatory) indicators for the environmental valuation of the Regional Master plan in the Paris metropolitan area (source: SDRIF fascicle 4).

Urban challenge	Indicators
Climatic change	Share of heavily artificial surfaces major geographical entity. Average annual consumption per ecosystem type converted into artificial surfaces.
Evolution of large landscapes and open spaces	Number of ecological continuities created or maintained. Number of non-fragmented patches per ecosystem type.
Natural and heritage resources	Sealing of agricultural areas. Share of edge of urbanized forest.
Health and well-being	Exposure of populations in areas at risk of flooding. Population exposed to noise levels >55 dB(A). Average public green spaces available per inhabitant.

sealing and ES to be studied in priority, ES indicators, have feedbacks on the produced results to discuss their relevance, and in some cases to modify the type of indicators produced or the type of modelling. Stakeholders' involvement in the process and modelling details (input sources, models' calibration and pre-processing) are summarized in table 2 and described in details in the SI section 3.

We defined the net soil sealing as the surfaces of natural, semi natural, open areas and urban parks converted to grey infrastructure, lowered by greening actions (grey infrastructure being converted into green ones) between two LCM versions. More precisely, soil sealing has been calculated as the LCM categories [1–27] converted into categories [29–81], termed 'artificial', during the 35 year period (refer to table S1 of the supplementary information document for the LCM detailed classification). The greening actions have been calculated by doing the reverse calculation, that is considering a greening action when categories [29–38] have been converted into [1–27]. Category 28 of the LCM (vacant land) was ignored from calculations, in order to consider only perennial conversions. Results give the net sealed or greened surface.

We used the Integrated Valuation of ES and Tradeoffs (InVEST 3.8) software to model groundwater recharge, climate regulation, water quality regulation, urban cooling, and flood risk mitigation (Sharp *et al* 2020). The models calculate and map the level of ES provided by each 100 × 100 m pixels according to an ecological production functions and spatialized local biophysical data (e.g. precipitations, albedo, topography, carbon stocks, or cultural coefficients). We developed our own GIS models for agricultural potential, outdoor recreation, and natural heritage. To evaluate the historical evolution of ES, we ran each of the models with the nine versions of the LCM covering the 35 year period with the 81 land cover classes (resulting in 72 maps). Results were finally aggregated at the municipal level and at the subwatershed level between 1982 and 2017.

2.3. Temporal and spatial matches between soil sealing and ES evolutions

Matches and mismatches between soil sealing and ES evolutions have been evaluated for temporal and spatial trends. The temporal mismatches are captured by changes in ES that do not follow the same trends as natural and semi-natural surfaces, i.e. where ES may be impacted by other types of land-use changes during the 1982–2017 period. The graphical interpretations of trends are tested with linear regressions evaluating the share of the each ES variance explained by net soil sealing evolutions.

Spatially, we considered a match between ES and soil sealing indicators when upward, downward or stagnant trends converge in polygons (e.g. net soil sealing and decrease in ES). The other cases are considered as mismatches, that is when the trends observed in polygons are reversed (e.g. net soil sealing and increase in ES) or when no evolution of soil sealing or ES is coupled with the evolution of the other (e.g. net soil sealing and no evolution in ES). These assumptions are summarized in table 3.

2.4. Spatial correlations between ES and soil sealing

In order to give a global overview of the spatial association between ES and soil sealing evolutions between 1982 and 2017, we computed Pearson product-moment correlation coefficient. Pearson's correlation, is a measure of the strength and direction of association that exists between two continuous variables. After checking for the linear relationship between the soil sealing and each ES, dropping significant outliers (13 outliers in total over 2359 polygons), and applied a Shapiro–Wilk test to ensure the normal distribution of variables[17], correlations and their significances were computed with the pwcorr command in STATA 14. We finally used Cohen's (1988) conventions to interpret effect size of the associations.

[17] The check of linear relationships and identifications of outliers was done with a scatter plot on STATA 14. Normality of the variable distributions is tested with the swilk command.

Table 2. ES indicators, key model inputs, units and changes suggested by stakeholders. LULC—land use/land cover.

ES	Indicator	Key model inputs	Unit	Changes suggested by stakeholders	Level of aggregation
Agricultural potential	Proportion of the agricultural surface at the municipal level	Agricultural surface, municipal surface	Share at the municipal level	—	Municipal level
Groundwater recharge	Potential contribution of the ecosystems to baseflow	LULC, monthly cumulative precipitations, monthly reference evapotranspiration, crop factor, slope, soil hydrologic groups, position of the pixel along the flow path, subwatershed boundary	Cubic meters per pixel	—	Sub-watershed level
Flood mitigation	Potential contribution of the ecosystems to reducing flood hazard	LULC, soil hydrologic groups, curve numbers, storm depth	Cubic meters per pixel	—	Sub-watershed level
Urban heat mitigation	Differences in Celsius degrees mitigated by urban vegetation during night time	LULC, local shade, evapotranspiration, albedo, green area maximum cooling distance, building intensity (capturing the vertical dimension of built infrastructure)	Celsius degrees per pixel	Consider the service only during nightime	Municipal level
Global climate regulation	Carbon stored in the different carbon pools of the ecosystems	LULC, carbon stored in the four main carbon pools (the soil, above- and below-ground biomass and dead organic matter)	Tons of carbon per pixel	—	Municipal level
Water quality regulation	Capacity of nutrient retention (N and P) by ecosystems	LULC, monthly cumulative precipitations, slope, subwatersheds, nutrient loads, maximum retention efficiency, critical length values, proportion of dissolved nutrients over the total amount of nutrients values	Kilograms per pixel	Consider constant nutrients loads over the period, 1982 as the base year	Sub-watershed level
Recreational potential	Proportion of green space of at least 1.5 ha within a radius of 300 m	LULC, position of housing pixel relatively to public greenspaces, population density per pixel	Share at the municipal level	Drop cemeteries, change the indicator of share of resident having access to a public greenspace of at least 1.5 ha within a distance of 300 m	Municipal level
Natural heritage	Suitable habitat for biodiversity, approximated with the probability to be classified as a ZNIEFF[18]	LULC, probability of a pixel to be classified as a ZNIEFF	Simulated hectares at the municipal level	Base the indicator only on ZNIEFF rather than on all types of protected areas	Municipal level

[18] Natural area of ecological, fauna and floristic interest (ZNIEFF), which is an inventory of natural resources launched since 1982 by the French Ministry of Environment and periodically revised. The data is made available by the National Inventory of Natural Heritage (INPN).

Table 3. Assumptions for defining matches and mismatches between soil sealing and ES evolutions between 1982 and 2017 in polygons.

	Increase in ES	No evolution in ES	Decrease in ES
Net greening	*Match*	Mismatch	Mismatch
No evolution	Mismatch	*Match*	Mismatch
Net soil sealing	Mismatch	Mismatch	*Match*

3. Results

3.1. Temporal evolution of soil sealing and ES during the period 1982–2017

Figure 2 presents key land-use changes observed in the period 1982–2017 in the Paris metropolitan area. Between 1982 and 2017, more than 400 km^2 of artificial surfaces were developed on natural and agricultural areas impacting primarily field crops. The sealing rate has however strongly decreased since 1987. From more than 12 km^2 of natural areas converted annually at the beginning of the period, the conversion reached 5 $km^2\ yr^{-1}$ at the end of the period. Despite this decline, soil sealing has been increasingly occurring on semi-natural areas, especially in the middle of the period (1994). In addition to soil sealing, important flows between meadows/semi-natural areas and ploughed lands describing the field/fallow cycles and crop rotations are observable. A strong conversion of agricultural areas into fallow lands is noticeable between 1990 and 2008, followed by an important reconversion of fallow land into agricultural areas from 2008. Forest cycles between logging and afforestation are more balanced in the period.

Figure 3 details the evolution of ES from 1982 to 2017. We also reported the evolution of natural and semi natural surfaces (categories 1–12 of the LCM), and parks and gardens (categories 13–27 of the LCM) for easier comparisons between trends. Even if different trends of ES appear, the region experienced an overall loss in all ES, except for a weak increase in the nitrogen capacity of retention. ES for which net soil sealing has the highest impact on variance are for agricultural potential, global climate regulation and urban heat island mitigation ($|\text{coeff}| > 0.34$, $r^2 > 0.5$, p-value $= 0.000$). However, contrarily to agricultural potential ($|\text{coeff}| > 1$, p-value $= 0.000$), global climate regulation and urban heat island mitigation decrease less than proportionally to the decrease of natural and semi natural surfaces. Regarding water related ES (i.e. water recharge, flood regulation and capacity of nutrient retention), no clear co-evolution with *in situ* soil sealing is noticeable ($r^2 < 0.2$, p-value $= 0.000$). This services are, in relative terms, little affected by the magnitudes of land use changes in the region[19]. Finally, recreational potential and natural heritage showed contrasting trends and have variances poorly explained by *in situ* soil sealing ($r^2 < 0.06$, p-value $= 0.000$).

3.2. Spatial evolution of soil sealing and ES

Table 4 shows the share of the Paris metropolitan area displaying matches and mismatches between net soil sealing and ES evolutions over 35 years. A match between the ES and soil sealing evolutions (as defined in table 3) is only observable in 10% of the surface of the Paris metropolitan area, while for 34%, a mismatch is observable for 5–8 ES. The majority of the matches concerns the occurrence of net soil sealing and ES losses. The more frequent mismatches accrue for natural heritage, recreational potential and water related services (∼50%–60% of the polygons, when this share is about 15% for other ES). Mismatches concerns principally municipalities and watersheds affected by soil sealing without incurring ES losses. Then, to a lesser extent, polygons having experienced urban greening and ES losses (occurring essentially in inner Paris city).

Figure 4 shows the spatial distribution of match and mismatches and appendix B the detailed maps of ES and soil sealing through the period 1982–2017. Figure 3 illustrates that the municipalities inside the city of Paris, the south and the east of the region have the strongest differences between ES evolutions and soil sealing. In general highest matches are found for high soil sealing rates (>9% change from 1982 to 2017). Highest mismatches (eight services) are found for net soil sealing rates ranging around zero ($\in [-3.5; 1.2]$) (appendix B). Matches/mismatches are not distributed totally independently from the size of the polygons (Prob $F < 0.05$), ranging from 1000 m^2 to 25 km^2, but this explains only 1.5% of the variance in matches and mismatches.

Regarding ES evolutions, as previously detected, a high heterogeneity between ES is observable. Strong decreases (<−20%) and strong increases (>20%) are observed for almost all ES aggregated at the municipal level, while small evolutions are observable for water-related services aggregated at the sub-watershed level (appendix B). Pearson's correlations (table 5) show that agricultural potential, global climate regulation and urban heat mitigation are strongly negatively correlated to soil sealing. Others ES have a moderate spatial correlation (groundwater recharge, flood

[19] According to the model results, the variations of these services range around ±0.3% (figure 3). In relative terms thus, the variation has been small over the period. In absolute terms, the change is not much more significant. For instance, the water recharge service decreased over the 35 year period by about 7.9 Mm^3 (our calculations) when 1315 Mm^3 are consumed annually by households, industry and farmers for irrigation (Seine-Normandie Water Agency).

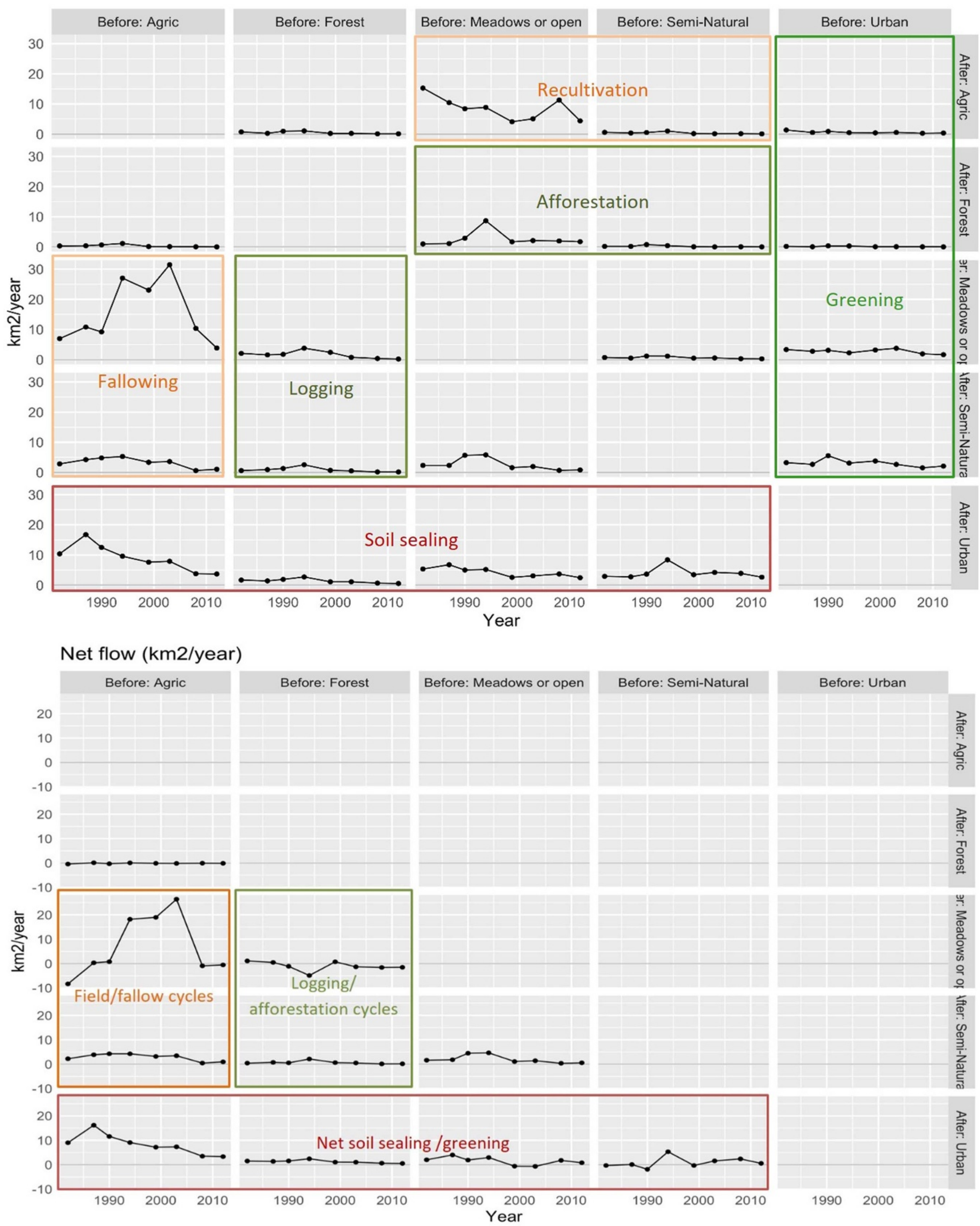

Figure 2. Gross (above) and net (below) flows between land cover categories in the Paris metropolitan area in $km^2\ yr^{-1}$ grouped by main LULC types between 1982 and 2017.

regulation, the capacity of phosphorus retention and natural heritage). Recreational potential and nitrogen retention capacity have the smallest strengths of association with soil sealing.

4. Discussion and conclusion

4.1. Soil sealing indicators alone do not explain all ES evolutions

Our results demonstrate that an important part of temporal and spatial changes in ES are not well captured by soil sealing indicators. Global climate regulation, agricultural potential and urban heat mitigation variations seems sufficiently predicted both in their spatial and temporal trends by sealing indicators. However, other variations in ES such as natural heritage, recreational potential, and water related services seem to be moderately tackled by sealing indicators both temporally and spatially. This can be explained by two main reasons, both of which argue in favour of a finer diagnosis of ES complementing soil sealing monitoring to evaluate past and future land use choices in impact evaluations.

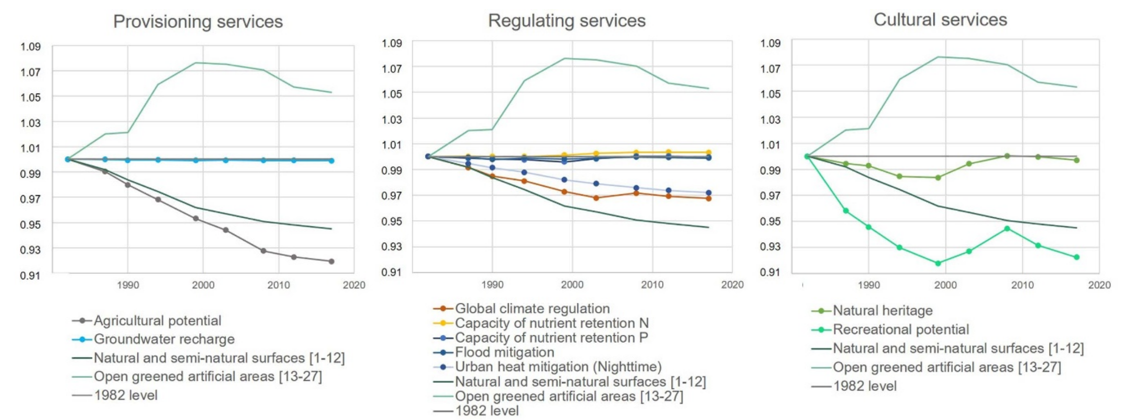

Figure 3. Changes in ES by LCM versions relative to their 1982 levels (reference year) for the three categories of ES.

Table 4. Matches and mismatches between soil sealing and ES evolutions.

	Match between soil sealing and eight ES evolutions	Mismatch between soil sealing and one to two ES evolutions	Mismatch between soil sealing and three to four ES evolutions	Mismatch between soil sealing and five to six ES evolutions	Mismatch between soil sealing and seven to eight ES evolutions
% of the area of the Paris metropolitan area	10%	30%	25%	27%	7%

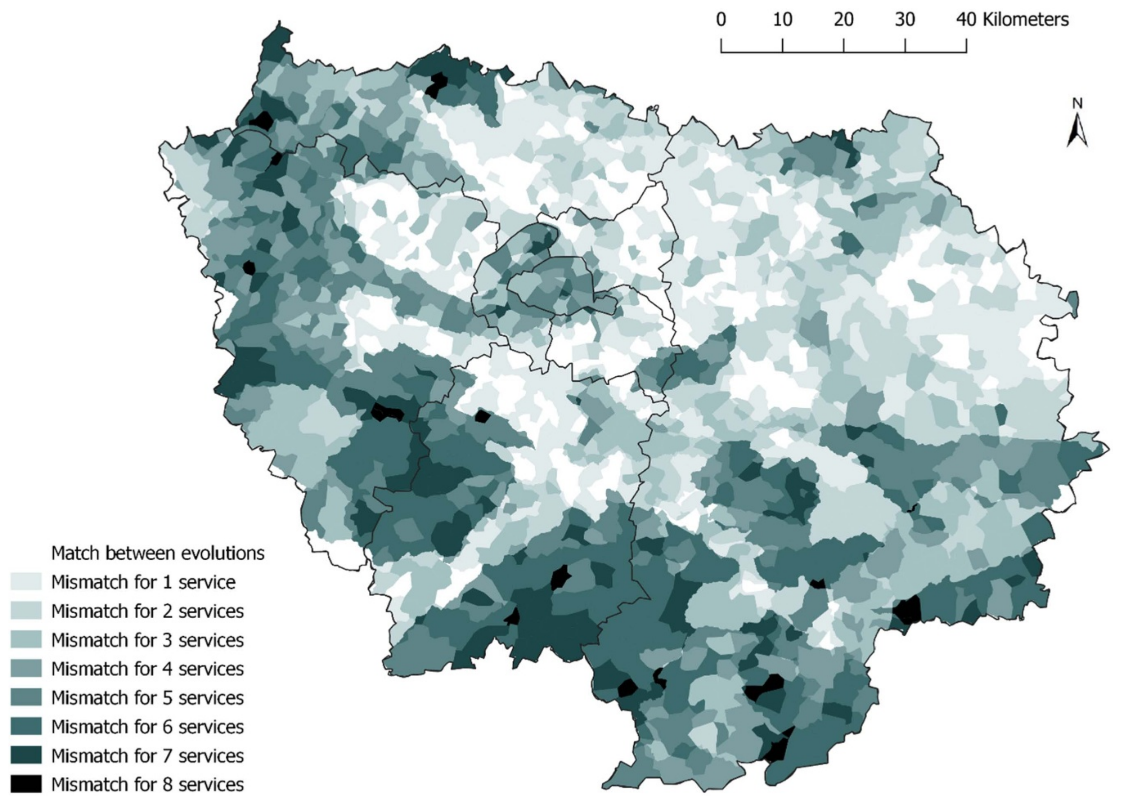

Figure 4. Matches and mismatches between soil sealing and ES evolutions beteween 1982 and 2017.

Table 5. Pearson (spatial) correlations between soil sealing and ES evolutions.

	Pearson correlations between soil sealing and ES evolutions	Strength of the association
Global climate regulation	−0.85[a]	Strong
Urban heat Island mitigation	−0.75[a]	Strong
Agricultural Potential	−0.59[a]	Strong
Water recharge	−0.39[a]	Moderate
Flood regulation	−0.36[a]	Moderate
Water quality regulation P	−0.33[a]	Moderate
Natural heritage	−0.30[a]	Moderate
Water quality regulation N	−0.16[a]	Small
Recreational potential	−0.11[a]	Small

[a] p-value <0.01, number of observations = 2346.

(a) ES losses or gains can be the results of other drivers of changes such as agricultural management practices (in the Paris metropolitan area, alternately cumulative and compensatory to soil sealing degradations).

Agricultural conversions, and particularly conversions between field (agricultural lands) and fallow (grasslands/meadows) play a predominant role in temporal variations in the ES supply, amplifying or compensating for losses due to soil sealing (figures 2 and 3). During the period 1990–2008, agricultural areas have been intensely converted to grasslands/meadows in the region, in response to the common agricultural policy (CAP) scheme of set-aside, first based on voluntary action in 1989, and then made compulsory in the 1992 reform for 10% of the arable land surface. These conversions have compensated partially the effects of soil sealing and implied important trade-offs between ES (e.g. loss of agricultural potential but increase in natural heritage and recreation). Then the abandonment of compulsory set-aside in 2008, following the surge in agricultural cereal prices in 2008 due to poor harvests, lead all ES to decrease. However, these conversions has been partially offset by the decrease of soil sealing even if the compensation has not been sufficient for the maintenance of ES, worsened by a decrease of gardens and parks surfaces. Even if these impacts may appear potentially as less perennials than sealing ones, agriculture remains a major factor in the degradation of biodiversity and ES delivering to societies (Pe'er *et al* 2014, 2019; Ipbes *et al* 2019, Butsic *et al* 2020). Encouraging less intensive farming practices with attractive agri-environmental schemes promoting high nature value farmland, or measures such as the establishment since the CAP 2015 campaign of areas of ecological interest[20] (EIS) (e.g. honey fallow, unbuilt ponds, buffer strips, cultivation in agroforestry) seem to be necessary strong measures to safeguard ES supply.

(b) ES losses are not necessarily co-located with soil sealing as some underlying ecological functions have a strong spatial dependency.

ES indicators represent a functional approach of socio-ecosystems. Ecological functions producing ES rely on different mechanisms depending on, for example, distances to residences, topography, connectivity between ecosystems, etc. Our results in table 4 and figure 4 suggest that impacts on ES may occur in other locations than the ones in where soil sealing pressures are observed. Monitoring soil sealing is thus crucial for environmental assessments of urban planning documents but likely to be insufficient to reflect ES losses at the landscape level. Current environmental indicators used to evaluate the regional master plan (table 1) alone cannot by themselves represent the ecological functionalities which urban dwellers depend on.

Given the challenge to handle the complexity of ecosystems in planning processes, the ES approach may help public policies to incorporate such ecological function information. The characterization of ES offers several advantages, such as the opportunity to measure and appraise the impact of different development designs and urban form on the relationship between ecosystems and human well-being (Albert *et al* 2014, Langemeyer *et al* 2016, Nin *et al* 2016). This additional information can help in promoting stakeholders' dialogue around important features of nature in cities and to move forward more inclusive planning (Hamel *et al* 2021; Liotta *et al* 2020, Ta *et al* 2020, Tardieu *et al* 2021).

4.2. Limits and research needs

In this paper, we analysed ES at the land use and land cover scale. Even if the LCM is a high-resolution dataset (25 m), it does not allow for characterising functional traits of species within an ecosystem (tree species for example), which would give refined indicators on ES. Some sealing actions may be overlooked with these types of data as it does not allow to apprehend

[20] Since 2015, the payment of decoupled direct aid has been conditional on compliance with environmental rules, the so-called 'greening' of the CAP. Greening represents the obligation for farmers to diversify their crop rotation, to define EISs (set at 5% of arable land), or to maintain their permanent pastures.

the urban mutations in detail, or impacts on ecological corridors of hedges and river banks. However, this does not compromise the scientific robustness of the analysis and the diagnosis of the match/mismatch with soil sealing indicators, since all indicators are calculated with the same dataset.

ES models limitations should also be acknowledged as well as the potential impact of conventions adopted here. All InVEST models used have limitations and simplifications which are described in the software documentation (Sharp *et al* 2020). However, uncertainty in absolute values are of secondary importance in our study since we focused on relative changes (temporally and spatially), for which the models are more robust (e.g. Bosch *et al* 2020, Hamel *et al* 2015, 2021). Further, InVEST models are computed with a 100 × 100 m pixel resolution to represent pixels of 1 ha, as almost all planning statistics in France are made at this level. Changing this resolution could have influence on the amplitude of ES changes, especially when reasoning the changes in absolute terms (Kandziora *et al* 2013). However, we think that this cannot change the main point of the paper (i.e. soil sealing indicators do not totally match the ES changes).

Concerning the bespoke models developed for this study, we note the following limitations. First, the agriculture ES indicator only reflected evolution in hectares dedicated to agriculture for each version of the LCM, regardless of the techniques used that could increase or decrease productivity (organic agriculture VS conventional agriculture for instance). These practices also could not be included in the calculation of the others ES, even if they have been approached by a detailed description of the main crops types present in the region with the LCM details. Second, the indicators were developed with stakeholders to input their knowledge, promote their understanding, and in turn their future implementation. However, the conventions adopted influences the results, such as the one adopted for recreation (recreational area of at least 1.5 ha within a radius of 300 m from residential areas). Even if the involvement of stakeholders favour the operationality of ES (Brunet *et al* 2018), it is important to make these conventions as transparent as possible during stakeholders meetings to facilitate discussions.

The assessment of ES has value in a participatory process because it allows diverse stakeholders to discuss the ES they consider at stake, modelled with meaningful indicators to them. It appeared that, in our case study, the three most pregnant ES in the urban settings were the urban heat mitigation, urban flood risks and recreational potential (section 2.2 and SI section 3.1). The ES considered at priority however may vary according to the socio-cultural, geo-climatic and economic contexts.

4.3. Conclusion

Despite the increasing recognition of the usefulness of incorporation of ES to better target sustainable urban development, their integration in urban land use planning is still in its infancy. Through consulting with urban planning stakeholders, we co-developed information on ES changes over time and space, showing that soil sealing, the indicator commonly used in strategic planning, contains a limited amount of information on ES evolutions. Soil sealing monitoring is therefore not sufficient to predict the impact of different planning decisions on major ecological functions in which urban citizens' well-being depend on. Incorporation of such information in urban planning documents would improve both environmental and societal outcomes of urban development.

Data availability statement

The major part of the data that support the findings of this study are included within the article (and any supplementary information files). The land use and land cover data (LCM) in 81 categories analysed during the current study is not publicly available but is available from the Institut Paris Region on reasonable request.

The data that support the findings of this study are available upon reasonable request from the authors.

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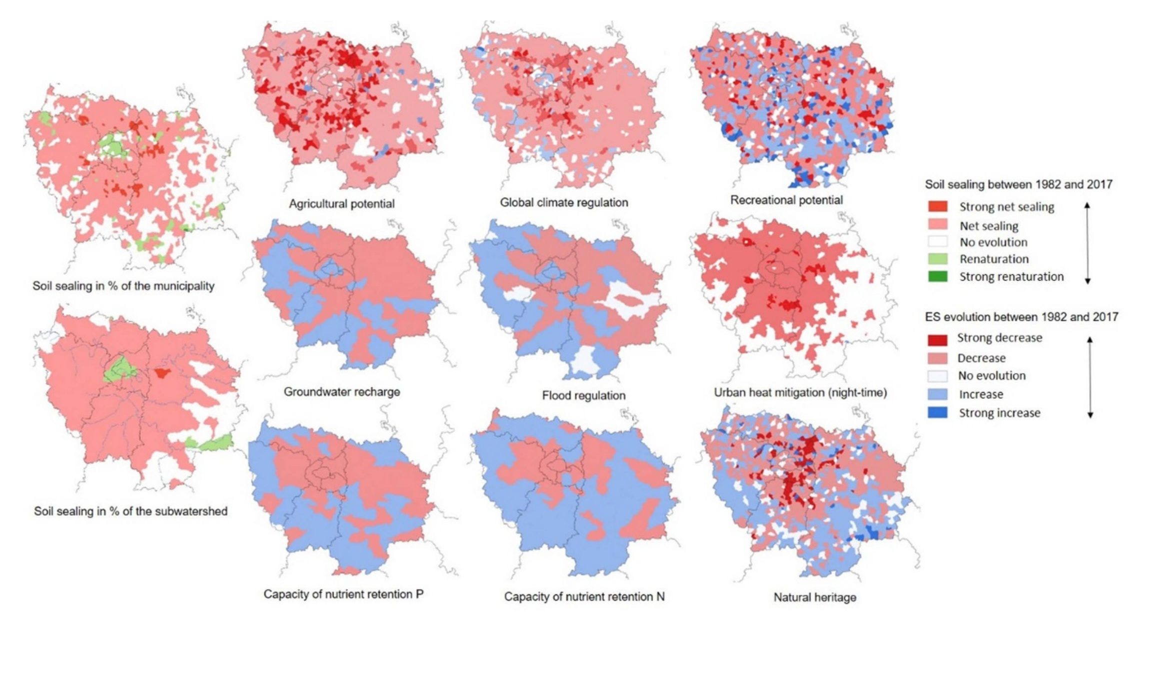
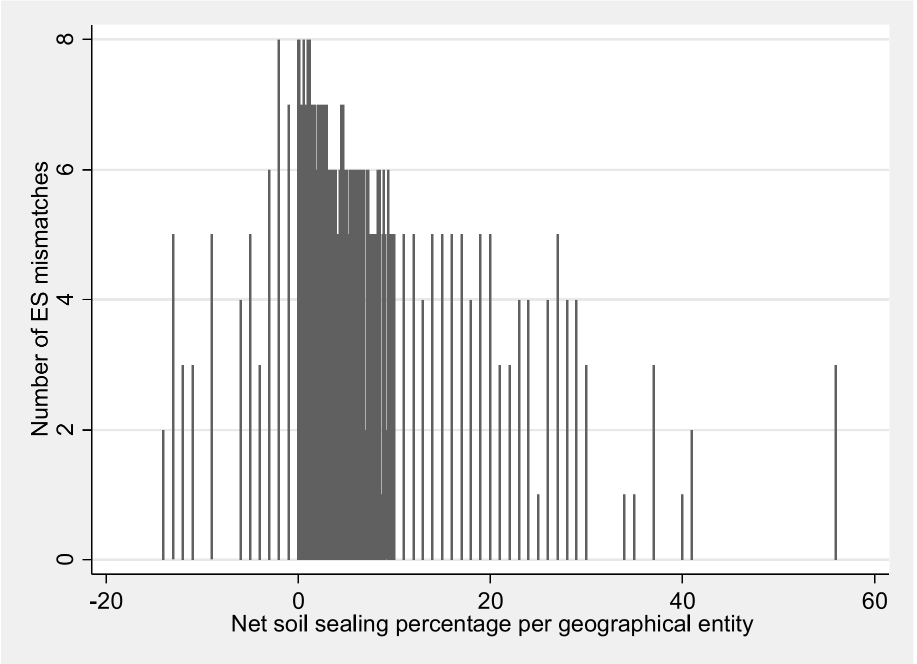
Appendix A. Stakeholders involved in the study

Institution type	Institution	Department (number of interviewees)
Administration ministry	French ministry of the environment	General commission of the sustainable development (three) General direction of planning, housing and nature (two) Urban planning, construction, development (one)
Decentralized state services	Interdepartmental regional directorate for equipment and planning	Development and land planning department (two) Urban planning documents office (one) Service of knowledge and prospective studies (one)
	Interdepartmental regional directorate of food agriculture and forest	Commission of preservation of natural, agricultural and forest areas (one) Regional service of forest, wood and biomass (two)
	Departmental directorate of territories	Planning department (two) Urban planning and regulations department (one)
Local authorities	Region Metropolis Municipality	Region Ile de France advisor (one) 'Grand Paris' advisor (two) Paris city advisor (one) City council (two) Urban planning department (one)
Regional assembly	Social and environmental economic advice	Committee on spatial planning and employment (one)
Agencies	Institute of urban planning	Department of urban and rural environment (one) Planning mission (one) Project managers (two)
	Natural park office National forest office Environment and Energy Management Agency Regional agency of biodiversity National agency for biodiversity French agency for development	Director (one) Project manager (one) Project manager (one) Project managers (two) Project managers (one) Project managers (one)
Groups	Chambers of agriculture Public interest group for forests	Project manager (one) Director (one)
Developers	Local planning and development authority Consulting agency	General directorate (one) Parisian agency (one)
Associations	France Nature Environnement Terres de liens European river network	Departmental federations (eight) Project manager (two) Project manager (one)
Think tank and scientific institutions	AgroParisTech Météo-France IDDRI	Ecology (one) Urban climatology (two) Political sciences (one)

Appendix B. Maps of soil sealing and ES evolutions between 1982 and 2017 per municipalities and sub watersheds; ES mismatches per net soil sealing percentages





Above: Net soil sealing in the Paris metropolitan area in percentage of the municipality/subwatershed (green represents a net greening) and evolution of ES aggregated at the municipal/subwatershed level; between 1982 and 2017.

Below: ES mismatches per net soil sealing ratios.

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