

The impact of projected increases in urbanization on ecosystem services

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Alteration in land use is likely to be a major driver of changes in the distribution of ecosystem services before 2050. In Europe, urbanization will probably be the main cause of land-use change. This increase in urbanization will result in spatial shifts in both supplies of ecosystem services and the beneficiaries of those services; the net outcome of such shifts remains to be determined. Here, we model changes in urban land cover in Britain based on large (16%) projected increases in the human population by 2031, and the consequences for three different services—flood mitigation, agricultural production and carbon storage. We show that under a scenario of densification of urban areas, the combined effect of increasing population and loss of permeable surfaces is likely to result in 1.7 million people living within 1 km of rivers with at least 10 per cent increases in projected peak flows, but that increasing suburban ‘sprawl’ will have little effect on flood mitigation services. Conversely, losses of stored carbon and agricultural production are over three times as high under the sprawl as under the ‘densification’ urban growth scenarios. Our results illustrate the challenges of meeting, but also of predicting, future demands and patterns of ecosystem services in the face of increasing urbanization.

Keywords: agricultural production; carbon storage; densification; flood risk; natural capital; urban ecology

1. INTRODUCTION

Alteration in land use is likely to be a major driver of global changes in the distribution of vital ecosystem services before 2050 [1]. Large increases in urbanization (conversion of land to residential and industrial areas) are in turn projected to be a key driver of these alterations in land use in many regions, and probably the main one in Europe [2]. These increases in urbanization are a consequence of growth both in the human population and in the percentage of that population living in urban areas—while globally only 220 million people (13%) lived in urban areas in 1900, this increased to 3.2 billion (49%) by 2005 and is projected to reach 4.9 billion (60%) by 2030 [3].

Urbanization will not only influence the potential supply and use of ecosystem services, but also the number, behaviour and distribution of potential beneficiaries of those services. For one, conversion of non-urban areas to urban areas is likely to reduce the supplies of many services. Secondly, increasing human populations could lead to shortages in some ecosystem goods and services (e.g. provisioning services such as agricultural production; [4]), even if there was no reduction in the overall quantity of service available, by decreasing the

amount available *per capita*. In addition, urbanization changes the distribution of beneficiaries: human populations are increasingly located in small dense patches (urban areas) that are frequently far away from where services are generated. This change in the distribution of populations relative to the locations of ecosystem service supplies could further reduce the *per capita* supply or increase the costs of service provision (e.g. dams and water transfers, transport of food from rural areas to urban areas). Finally, these multifaceted interactions between urbanization and ecosystem service provision are likely to alter trade-offs between services in an area (e.g. [5]). However, analyses of such interactions have been lacking to date.

While many ecosystem services will be affected by urbanization, mitigation of the impact of freshwater flood events by the landscape (through storage and slow release of rain water from the soil and aquifers) is a vital ecosystem service that can be particularly severely affected by increases in urbanization. This is because (i) urban development can lead to larger and more frequent floods owing to increases in impervious surfaces (reviewed in [6]), and (ii) the increasing population of growing urban areas leads to more people being affected by floods.

Here, we provide the first study mapping the impacts of projected increases in urbanization on a range of ecosystem services at a national scale by assessing the effects of two contrasting urbanization scenarios on

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freshwater flood mitigation services, carbon storage and agricultural production for Britain. Specifically, we link spatially explicit urbanization projections for the period 2006–2031 with estimates of peak river flows from a high-resolution hydrological model, and with existing spatial models of stored carbon and agricultural production. We chose Britain as a case study because of (i) the availability of the high-resolution, national-scale datasets required for this sort of analysis and (ii) the high (16%) projected increase in the human population by 2031 (<http://www.statistics.gov.uk/pdffdir/pproj1007.pdf>).

We compare two urbanization scenarios in our analyses that reflect opposite ends of the spectrum of urban growth scenarios that are likely to occur in Britain as a result of projected increases in population growth. Under one strategy, expansion of future urban areas is minimized by increasing the density of existing dense urban areas (hereafter the ‘densification’ scenario), while under the other, overall urban area increases by favouring future urban growth at the same densities as existing suburban areas in Britain (hereafter the ‘sprawl’ scenario). There has been a policy of increasing densification in the UK since 2000 [7], which has led to increased housing density [8], suggesting that densification is a realistic scenario. However, patterns of urbanization are sensitive to both economic conditions and planning policy [8], and growth similar to the sprawl scenario is in line with one of the (non-spatial) housing scenarios developed for England by the UK government [9].

2. METHODS

Our study takes advantage of a national-scale hydrological model for Britain [10], and of spatially explicit population projections for the period 2006–2031, together with existing high-quality datasets available for two ecosystem services (agricultural production and stored carbon; [11]).

(a) *Ecosystem services*

(i) *Flood mitigation*

While mapping areas at a high risk of flooding (currently and in the future) is relatively straightforward and often carried out by national governments (e.g. the Foresight Future Flooding study for Britain; [12]), actually identifying which portions of a landscape provide flood mitigation services is a much more complex undertaking. This is both because of the need spatially to link upstream locations where the service is being provided with downstream beneficiaries, and because of the difficulties in linking specific land cover types to flooding. A spatial hydrological model is required to link changes in run-off upstream caused by changes in natural land cover to changes in peak flows downstream. This in turn needs to be linked to the number of people who would be affected by changes in peak flows—if there are no direct or indirect beneficiaries of landscape flood mitigation, there is no ecosystem service. However, while maintenance of natural land-cover types such as forests or wetlands can lead to reduced peak flows further downstream through direct use (e.g. [13]) and by facilitating infiltration (e.g. [14,15]), the link between different types of land cover and flooding is very difficult to quantify at anything other than a local scale [16].

A number of studies have mapped flood mitigation/flood control within the ecosystem service framework, but these

have in the main been restricted to mapping land-cover types that *can* reduce flooding (e.g. [17,18]), or to simple models that map flood risk based on biophysical factors such as slope and elevation (e.g. [19]). A few studies combine multiple factors in identifying key areas for flood mitigation in large-scale studies (see e.g. [20,21] globally), but no large-scale study to date has used a hydrological model explicitly to link upstream changes in flows to downstream beneficiaries.

Here, we used an existing grid-based hydrological model (Grid-to-Grid (G2G) [10]) of Britain to map the impacts of projected changes in dense urban and suburban land cover between 2006 and 2031 on freshwater flood mitigation services provided by the landscape. We quantify loss of flood mitigation provided by the landscape that the hydrological model predicts will occur through the conversion of non-urban land to urban land by calculating the change in flood risk (percentage increase in peak flow at the 2 year return period) for 1×1 km UK grid squares containing a significant river component (grid squares with a drainage area greater than 20 km^2 or for which the observed river length is greater than 500 m). A 2 year return period peak flow denotes the magnitude of flow that would be exceeded on average every 2 years and corresponds to the median annual flood. This value will typically be slightly higher than bankfull flow, which is the maximum amount of discharge that a river channel can accommodate without overflowing. For a 2 year return period of flow (*without* any additional increase), we would expect some localized flooding of natural river reaches that have no artificial flood defences. Preliminary analyses (electronic supplementary material) showed that using a 20 year return period rather than a 2 year return period did not qualitatively affect our findings.

The G2G model is a grid-based hydrological model whose main output is time-varying grids of river flow across a large region, in this case Britain. The model requires gridded estimates of precipitation and potential evaporation (PE) as input, and has previously been used to assess how climate change may impact river flows [10] and to estimate real-time river flows for operational flood-forecasting [22]. G2G relies on digital datasets of landscape and soil properties to provide the spatial differentiation in landscape response to rainfall, and a recent evaluation comparing modelled and observed river flows at sites across Britain indicated relatively good model performance [10]. More accurate simulations can be obtained by model calibration to individual catchment conditions (e.g. abstractions, presence of reservoirs), but the emphasis here is to study large-scale hydrological changes, for which this model is ideally suited. Further details of the G2G model formulation and a map of peak flows across Britain (see electronic supplementary material, figure S1) are available in the electronic supplementary material.

(ii) *Agricultural production*

Following Anderson *et al.* [11], we measured agricultural production as the summed gross margins of all major crops and livestock, at the 1×1 km grid resolution (see electronic supplementary material, figure S3). We obtained raw yields in relevant units (e.g. animals per hectare) from agricultural census data from England [23], Scotland [24] and Wales [25]. We then converted these yields into gross margins using estimates obtained from the Farm Management Handbook 2007/2008 [26]. Gross margins (value of output – variable costs excluding subsidy payments) provide the best estimate

of yield that the ecosystem can provide by allowing us to exclude human-applied inputs such as fertilizer. See the electronic supplementary material for detailed methods.

(iii) Carbon storage

Also following Anderson *et al.* [11], we obtained estimates of the total above and below ground (vegetation and soil) stored carbon per 1×1 km grid cell (see electronic supplementary material, figure S4). Vegetation carbon data were obtained from Milne & Brown [27], while soil carbon data were estimated from extensive field, soil parameter, land-use and soil series data. Detailed methods can be found in the electronic supplementary material.

(b) Future urbanization models

We created simple models of projected urbanization in 2031 for Britain that highlight opposite ends of the spectrum of urban growth scenarios that are likely to occur as a result of projected increases in population growth—the densification and sprawl scenarios. We could not use existing models of future land-use change as even the most spatially resolved of these for Britain as a whole [28] does not give the percentage of each 1×1 km grid square that is covered by dense urban and suburban land cover required by our hydrological model [10]. Our urbanization models take advantage of recent district-level projections of population growth for Britain combined with land-cover data (Land Cover 2000: [29]). These population projections are available online through the Office of National Statistics for England (<http://www.statistics.gov.uk/statbase/product.asp?vlnk=997>), the General Register Office for Scotland (<http://www.gro-scotland.gov.uk/statistics/publications-and-data/popproj/index.html>) and StatsWales (http://www.statswales.wales.gov.uk/ReportFolders/reportfolders.aspx?IF_ActivePath=P,345,1851,2048,5954). The districts (or local authorities) range from small, densely populated areas (e.g. the London borough of Westminster) to moderately sized cities with intermediate population densities (e.g. Sheffield) to large, sparsely populated rural districts (e.g. the Scottish Highlands). Note that our urbanization model also calculates the projected number of people in each 1×1 km grid square, in addition to the percentage of each grid square that is covered by dense urban and suburban land cover.

Under the densification scenario, the housing demands of the projected increases in the population in each district are preferentially met by converting existing suburban housing to dense urban housing. Suburban housing has approximately 65 per cent of the population density of dense urban housing (3298 versus 5052 km^{-2} , as calculated for England, which has approx. 85% of the population of Britain), so 35 per cent more people can be accommodated in dense urban areas than in suburban housing. New housing (also at dense urban and not suburban population densities) is only added under the densification scenario once all suburban housing in a district has been converted to dense urban housing, therefore minimizing the need for new urbanization.

Under the sprawl scenario, the opposite occurs—housing demands are preferentially met by creating new housing at suburban housing densities, with conversion of suburban to dense urban housing only occurring when no space is available in the district for new urbanization (e.g. parts of London). In both scenarios, new housing is preferentially located near existing urban areas, and is restricted to ‘realistic’ locations;

that is, not in National Parks, biodiversity reserves, nationally important historic sites, large city parks, wetlands or montane areas.

We also modified both the densification and sprawl scenarios to minimize the losses of stored carbon and agricultural production, respectively, by preferentially placing new urban areas in 1×1 km grid cells with low levels of the respective service; similar analyses minimizing losses of flood mitigation services were not undertaken as they are beyond the scope of this manuscript (see electronic supplementary material). We then evaluated the effects that these ‘minimization of loss’ scenarios had on flood mitigation. All GIS analyses were carried out in ARCGIS/ARC/INFO 9.2 (ESRI, Redlands, CA, USA), and urbanization modelling and all statistical analyses were carried out in R 2.10 [30]. Detailed methods about the creation of and the assumptions within the future urbanization model are available in the electronic supplementary material, along with a map of the distribution of the current cover of suburban and urban land cover (see electronic supplementary material, figure S5).

(c) Integration of ecosystem service and urbanization models

(i) Flood mitigation

The extent of impervious urban cover is an important factor determining the effect of urban development on peak river flows. Impervious urban surfaces (e.g. roads and buildings) reduce the infiltration of rainfall to soil/groundwater stores and increase fast surface run-off. In the G2G model, urban extent is divided into two categories, urban and suburban, for which relatively simple differences in hydrological behaviour are assumed. For grid cells containing an urban or a suburban fraction (based on the 25×25 m resolution LCM2000 land-cover map; [29]), the amount of water stored by soils is reduced to a value below that specified by national soil datasets, with the greatest reduction applied in urban areas. The specific reduction factors used in the G2G model for dense urban and suburban pixels (70 and 30%, respectively) have been determined through a combination of model assessment and calibration for catchments containing a significant urban fraction [10], and literature recommendations. For example, assuming the same soil type, conversion of 50 per cent of a 1×1 km grid cell to dense urban or suburban land cover would result in a loss of 35 and 15 per cent of the water storage capacity of the grid cell, respectively. Typically, rivers with large projected increases in flooding are those that are located downstream from clusters of urbanized cells for which the water storage capacity has been reduced.

(ii) Agricultural production

We assumed that agricultural production would be reduced at a rate directly proportional to the amount of new urbanization (dense urban or suburban) in a 1×1 km grid cell. For example, if agricultural production in a grid cell was originally estimated to be £1000, and 25 per cent of the cell was then projected to urbanized, then this would result in production in the square being reduced to £750; this assumption may not always be true because of economies of scale. This approach also assumes that urban areas have no agricultural production, that new urban areas will primarily occur on agricultural land and that agricultural prices, preferences and productivity are static. The first assumption is likely to be broadly correct, given that agriculture in Britain

Table 1. Number of people residing within $1 \times 1 \text{ km}^2$ that have projected increases in peak flows (2 year return period) under the densification and sprawl scenarios of urban growth by 2031.

minimum percentage increase in peak flow	densification		sprawl	
	people	percentage of population	people	percentage of population
10	1 736 000	2.5	11 000	0
20	774 000	1.1	1000	0
50	180 000	0.3	0	0

Table 2. Losses in carbon storage and agricultural production (percentages of total for Britain) under the densification and sprawl urbanization scenarios.

service	densification scenarios			sprawl scenarios		
	base	minimize losses of agricultural production	minimize losses of stored carbon	base	minimize losses of agricultural production	minimize losses of stored carbon
carbon storage	0.20	0.22	0.16	0.71	0.77	0.61
agricultural production	0.32	0.15	0.42	1.12	0.60	1.36

is heavily mechanized and dominated by large-scale operations that do not occur in urban areas. The second assumption is probably also broadly correct in Britain, given that most areas that are suitable for urbanization (i.e. not wetlands or moorland) are also farmlands (only 12% of Britain is forested; [8]). The third assumption of static prices, preferences and productivity is clearly not true, but is unavoidable given (i) the complexities of predicting future shifts in agricultural prices and preferences and (ii) the lack of availability of such data for Britain as a whole.

(iii) Carbon storage

We assumed that new urbanization would affect stored carbon exactly as for agricultural production—stored carbon would decrease at a rate directly proportional to the amount of new urbanization (dense urban or suburban). Again, this approach assumes that urban areas have no stored carbon. This is almost certainly an underestimate of true carbon stores, but is in line with many current national estimates of soil [31] and vegetation [27] carbon for Britain, owing to a paucity of data on carbon stores in urban areas.

3. RESULTS

The high (16%) projected growth in the British population by 2031 will have a considerable impact on the three ecosystem services considered here. However, which services will be most affected will depend critically on whether future urbanization patterns are closer to densification or to sprawl scenarios of urban growth—there is a much greater negative effect on natural flood mitigation services under the former, while carbon storage and agricultural production see larger reductions under the latter (tables 1 and 2).

There are large differences in the amount of land converted to new urbanization (figure 1), and differences in the increased amount of dense urbanized areas (figure 2), between the two scenarios. The total amount of land converted to new urbanization is 948 km^2 (0.4% of Britain) and 3302 km^2 (1.4% of Britain) under the densification

and sprawl scenarios, respectively. Dense urban area is projected to increase by 94 per cent (from 4170 to 9161 km^2) under the densification scenario, but only by 2 per cent (4170 – 4787 km^2) under the sprawl scenario. Modification of the densification and sprawl scenarios to minimize losses of stored carbon or agricultural production, respectively, had no effect on the amount of land converted to new urbanization or in the amount of dense urban land. This is because these ‘minimization’ scenarios primarily shifted where new urbanization occurred, and not the total amount of land converted to new urban areas or the areas converted to dense urban.

The densification scenario has a much greater effect on increases in flood risk caused by a loss of natural flood mitigation services than the sprawl scenario (figure 2). The mean change in peak (2 year return period) flows across all British rivers is relatively small in both, but over three times higher under the densification scenario (1.4%; s.d. of 6.3 percentage points) than under the sprawl scenario (0.3%; s.d. of 0.65 percentage points). However, much higher changes are projected to occur near or downstream of many urban areas under the densification scenario (figure 2). The difference between the scenarios is even more pronounced when the beneficiaries of flood mitigation services are considered. Under the densification scenario, approximately 1.7 million people (as calculated from the urbanization model) would reside within the same $1 \times 1 \text{ km}^2$ for which peak river flows are projected to increase by at least 10 per cent, whereas under the sprawl scenario, a much smaller number of people (approx. 11 000) would be affected in this way (table 1).

For carbon storage and agricultural production, losses in the current stock of both services will be 3.5 times higher under the sprawl than the densification scenario (table 2). Modification of the scenarios to minimize losses of agricultural production approximately halves losses of agricultural production at the expense of an 8–10% increase in the amount of carbon lost. However, minimizing losses of carbon only leads to a 15–20%

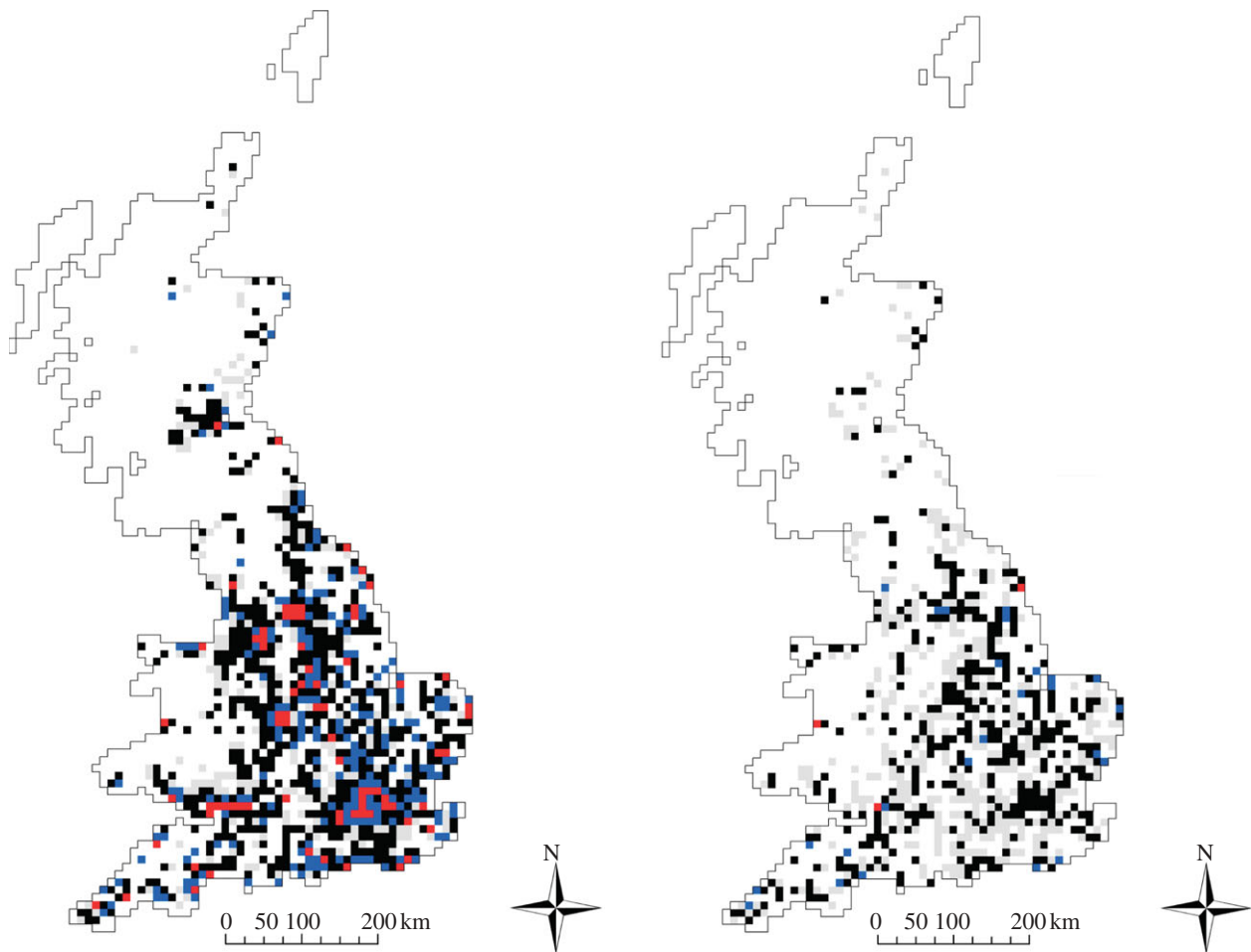


Figure 1. The percentage of each 1×1 km grid cell (mean value per 10×10 km cell) projected to be converted from non-urban to urban (dense urban + suburban) by 2031 in Britain under the densification and sprawl scenarios (unshaded area, 0; grey-shaded area, 0–1; black-shaded area, 1–5; blue-shaded area, 5–10; red-shaded area, 10–22).

reduction in the amount of carbon lost at the expense of a 20–25% increase in losses in agricultural production (table 2). Minimization of losses of stored carbon or agricultural production also leads to small increases in the number of people predicted to be affected by peak flows under the densification scenario (approx. 2% more people affected by at least 10% increases in peak flows). Under the sprawl scenario, the absolute number of people likely to be affected is still very small (approx. 16 000 affected by at least 10% increases in peak flows under the minimization of losses in agricultural production/sprawl scenario versus 11 000 under the base sprawl scenario). However, these small changes in numbers can translate to large (up to 100%) percentage increases in the number of people likely to be affected by changes in peak flows when minimizing losses of stored carbon or agricultural production under the sprawl scenario (see electronic supplementary material, table S2).

4. DISCUSSION

The results of our models suggest that the best type of urban development in terms of maintaining ecosystem services will depend on the service considered, highlighting the challenge both of predicting and sustainably managing ecosystem services under changing land-use patterns. For example, future shifts in both the amount and distribution

of ecosystem service supplies and beneficiaries could alter current patterns of covariation between ecosystem services (e.g. [11,20]) and existing ‘ecosystem service bundles’ [32]. Indeed, the complexity of the relationships between just three ecosystem services under just two land-use scenarios presented here emphasizes the importance of understanding the drivers of relationships between different ecosystem services [5].

A key finding of this study is that increasing sprawl-type, suburban development potentially has less of an effect on flood mitigation services than increasing the amount of dense urban housing, but that the opposite is true for stored carbon and agricultural production. The much greater increase in risk of flooding was due to the doubling of dense urban areas (mostly through conversion of suburban areas to dense urban areas) under the densification scenario. In the hydrological model applied here, high-density housing (dense urban) development leads to a greater reduction in subsurface water storage than low-density (suburban) housing, and to increases in river routing speed. This decreases the residency time of water, and leads to a faster release into rivers, which in turn increases peak flows and downstream flooding [14]. Losses of stored carbon and agricultural production were predicted to be higher in the sprawl scenario than in the densification scenario because over three times as much non-urban land was converted to urban in the

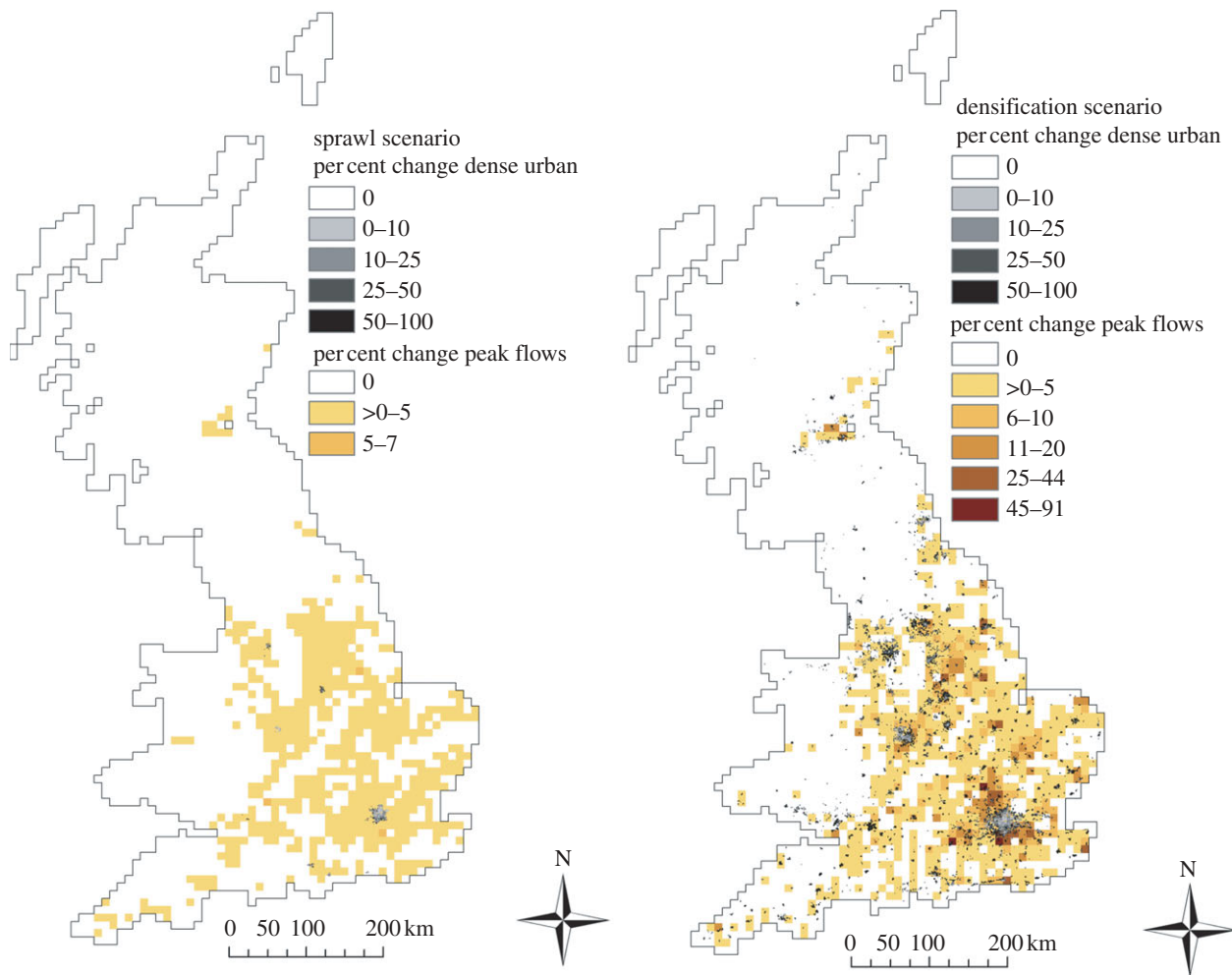


Figure 2. Projected changes in peak flows at the 2 year return period (10×10 km grid cell resolution) by 2031 for Britain under the densification and sprawl scenarios. The percentage of dense urban land cover (1×1 km resolution) is shown for reference.

former than in the latter. It is important to note that our models assume static societal preferences for the ecosystem services we consider, which is unlikely to be true. For example, increases in the risk of flooding may lead to some areas no longer being considered suitable for housing. This would reduce the number of people affected by increased flooding, but would inevitably increase development pressure on other areas.

More generally, this study highlights the challenges in predicting future impacts of urbanization on ecosystem services in general, and on hydrological services in particular. Our study uses the state of the art in large-scale hydrological modelling—the G2G model [10]—explicitly to link upstream changes in flows to downstream beneficiaries, but nonetheless we were forced to make a number of pragmatic simplifying assumptions owing to the lack of research on the effects of urban development on large-scale hydrology. The most important assumption—that dense urbanization results in a 70 per cent reduction in soil storage while suburban housing only reduces soil storage by 30 per cent (assuming the same underlying soils)—is in line with current hydrological understanding, but clearly future changes to urban drainage systems or developments in large-scale urban modelling could lead to significantly different findings from what we report here.

If methods can be found for increasing urban densities without compromising flood mitigation services, then the

advantages of increasing densification are considerable. Indeed, if it were possible to accommodate the projected population growth in Britain by increasing the population density of urban areas by 50 per cent beyond the densities currently found in dense urban areas, then only 56 km^2 of land would need to be converted to new urban areas (versus 948 and 3302 km^2 under the densification and sprawl scenarios, respectively) (see electronic supplementary material). Densification also leads to more efficient energy and resource use [2,33]. Technological innovations such as increased use of sustainable urban drainage systems (e.g. permeable pavements, urban storage ponds) encouraged by building regulations could potentially mitigate the loss of subsurface storage in new urban developments, leading to lower increases in peak flows, while improved flood defences could minimize the damage caused by such flows. As such innovations may be particularly cost-effective in dense urban development, they could allow high levels of urban densification, while still reducing the impact of flooding in dense urban relative to low-density urban development. Innovative planning solutions such as green roofs [34] could also offset the losses of urban green space currently associated with high urban housing densities in Britain [35]; urban green space can provide direct positive effects on the health of local human populations (e.g. [36]) in addition to providing other ecosystem services (e.g. [35,37]). However, recent experience suggests that

such low-impact densification is likely to be challenging; the recent policy of densification [7] in England has meant that the proportion of new dwellings built on previous residential land in England has risen from 12 to 27 per cent between 1999 and 2009, leading to considerable public concern about the conversion of residential gardens to housing—‘garden grabbing’ (<http://www.communities.gov.uk/news/newsroom/1665648>).

Careful selection of where new urbanization occurs may also offer some solutions to the trade-offs between ecosystem services under different types of urban growth. Indeed, we show that by shifting the locations of new urban areas, losses in agricultural production can be halved at the cost of only a 10 per cent increase in losses of stored carbon, with relatively little effect on flood risk. However, reliably to inform policy, models such as ours should include a much wider set of services, or risk potentially catastrophic losses of vital services whose spatial distribution is currently unknown.

Our analysis also illustrates that linking future supplies of ecosystem services to changes in the number and distribution of beneficiaries is vital to making informed policy decisions. In our study, the actual percentage of the total supply of ecosystem services that is affected by projected increases in urbanization is relatively small. This is because even under the sprawl scenario, a 16 per cent increase in human population only translates into an extra 1.5 per cent of Britain being converted from non-urban to urban land cover. However, these small percentage changes can have major socioeconomic impacts, particularly because of the projected increase in the human population.

For example, we show that despite the relatively low mean increases in peak flows across all rivers, under the densification scenario, 1.8 million people could be living in areas with projected increases of at least 10 per cent in peak river flows at the 2 year return period. While it is very unlikely that all these people would actually be affected by flooding (given that we only have data at the 1×1 km grid resolution, and not all areas would flood), even if flooding affected an extra 18 000 people (1% of this total) every 2 years, this would have very high human and economic costs. The total economic cost of flooding in England in 2007, which affected between 46 000 and 48 000 households, was estimated to be £3.2 billion [38].

The increasing human population also increases the potential policy impact of even small losses in agricultural production, as such production actually needs to increase to maintain current levels of self-sufficiency. Even a 1.1 per cent reduction in agricultural production combined with a 16 per cent increase in the population will mean that self-sufficiency will drop from approximately 57 to 48 per cent by 2031 in Britain (electronic supplementary material). Until recently, self-sufficiency has not been a major UK government priority, based on the argument that the financial wealth of the country means that it is well placed to import food as needed. However, this policy could potentially change quickly [39], and indeed the financial crisis of 2009 has already led to suggestions that arguments against increasing self-sufficiency are no longer politically or economically credible (e.g. [40]).

The policy implications of any losses of stored carbon are magnified by the UK’s legally binding targets under the 2008 Climate Change Act (<http://www.opsi.gov.uk/acts/>

[acts2008/pdf/ukpga_20080027_en.pdf](http://www.opsi.gov.uk/acts/acts2008/pdf/ukpga_20080027_en.pdf)) to reduce annual carbon emissions by 2020 by 34 per cent from 1990 levels, and 80 per cent by 2050. A loss of 0.7 per cent of the total carbon stock of Britain is approximately equal to 17 per cent of the total carbon emitted in Britain in 2008 (electronic supplementary material), and, even if it occurs over 25 years, such extra releases of carbon would make difficult overall reductions in carbon emissions yet more so.

More generally, these first projections of the interactions between land-use change and human population growth we describe for Britain have major implications for conserving ecosystem services globally. The combination of an increasing number of human beneficiaries of ecosystem services and increasing competition for the land that provides these services is a worldwide phenomenon for which the policy implications are only now beginning to be considered. Quantifying the impacts on both the supply and demand side of ecosystem services under realistic future land-use change scenarios is urgently needed to identify those services for which future shortages are most likely; and whether and where strategies can be devised to minimize losses of ecosystem services. Such work will require innovative collaborative efforts between physical, ecological and social scientists to develop the new models that will be required to reliably model the ecosystem service impacts of both an increasing human population and changes to ecosystems driven by land use and climate change.

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