Bringing Ecosystem Services into Economic Decision-Making: Land Use in the United Kingdom

Ian J. Bateman,[1]* Amii R. Harwood,[1] Georgina M. Mace,[2] Robert T. Watson,[3] David J. Abson,[4,5] Barnaby Andrews,[1] Amy Binner,[1] Andrew Crowe,[6] Brett H. Day,[1] Steve Dugdale,[1] Carlo Fezzi,[1] Jo Foden,[7] David Hadley,[1,8] Roy Haines-Young,[9] Mark Hulme,[10] Andreas Kontoleon,[11] Andrew A. Lovett,[1] Paul Munday,[1] Unai Pascual,[11,12] James Paterson,[13] Grischa Perino,[1,14] Antara Sen,[1] Gavin Siriwardena,[10] Daan van Soest,[15] Mette Termansen[16]

Landscapes generate a wide range of valuable ecosystem services, yet land-use decisions often ignore the value of these services. Using the example of the United Kingdom, we show the significance of land-use change not only for agricultural production but also for emissions and sequestration of greenhouse gases, open-access recreational visits, urban green space, and wild-species diversity. We use spatially explicit models in conjunction with valuation methods to estimate comparable economic values for these services, taking account of climate change impacts. We show that, although decisions that focus solely on agriculture reduce overall ecosystem service values, highly significant value increases can be obtained from targeted planning by incorporating all potential services and their values and that this approach also conserves wild-species diversity.

The Millennium Ecosystem Assessment (*1*) provided important evidence of the ongoing global degradation of ecosystem services and highlighted the need to incorporate their value into the economic analyses that underpin real-world decision-making. Previous studies have shown that the overall values of unconverted natural habitats can exceed the private benefits after conversion (*2*, *3*); that knowledge of landscape heterogeneity and ecological processes can support cost-effective land planning (*4*–*7*); that trade-offs in land-use decisions affect values from ecosystem services and biodiversity at the local level (*8*, *9*); and that current land use is vulnerable to the impacts of global change (*10*, *11*). In the UK National Ecosystem Assessment (NEA) (*12*), a comprehensive assessment of the United Kingdom's ecosystems was linked to a systematic environmental and economic analysis of the benefits they generate. Here, we show how taking account of multiple objectives in a changing environment (including, but not restricted to, climate change) fundamentally alters decisions regarding optimal land use. The NEA analyses are based on highly detailed, spatially referenced environmental data covering all of Great Britain. These data supported the design and parameterization of models of both the drivers and consequences of land-use decisions, by incorporating the complexity of the natural environment and its variation across space and time (*13*). Model outputs provide inputs

Table 1. Summary of the ecosystem service related goods considered in the analysis. [Metrics, data, modeling and valuation are fully documented in (*13*).]

Ecosystem service–related good	Metrics (in year specified)	Main data and sources	Model	Valuation
Agricultural production	Proportion and output of land use in each 2-km grid square	Land use, soils and physical environment, climate, digital mapping, etc. (*31*–*33*)	Environmental-econometric regression analysis of land-use decisions as a function of the local physical environment, prices, costs and policies, based on (*34*)	Market values (*35*)
Greenhouse gases	Net metric tons of CO_2, CH_4, and N_2O per 2-km grid square	Land-use predictions, GHG responses (*36*–*38*)	Process models for CO_2, CH_4, and N_2O; conversion to metric tons of CO_2 equivalent ($MTCO_2Eq$) based on insulation factors	Official UK values per $MTCO_2Eq$ (*39*)
Recreation	Visitors per 2-km grid square	National survey of >40,000 households, census (*40*, *41*)	Regression model of visit count from outset to destination as a function of characteristics of both locations, population socioeconomics, etc.	Meta-analysis of 300 ecosystem-specific valuation estimates
Urban green-space amenity	Distance to green space from each 2-km grid square	Digital mapping census (*32*, *41*)	Regression model linking distance from households to green-space sites, their size and quality	Meta-analysis of prior literature examining changes in value with respect to distance
Wild bird–species diversity	Wild bird diversity (*20*) per 2-km grid square	*Breeding Bird Survey* (*42*)	Regression model linking wild bird diversity to land use and location.	Not valued; analysis uses the opportunity cost of avoiding declines

---

[1] Centre for Social and Economic Research on the Global Environment (CSERGE), School of Environmental Sciences, University of East Anglia (UEA), Norwich Research Park, Norwich, NR4 7TJ, UK. [2] Department of Genetics, Ecology and Environment, University College London, London WC1E 6BT, UK. [3] Tyndall Centre, Department of Environmental Sciences, University of East Anglia, Norwich Research Park, NR47TJ, UK and Monash Sustainability Institute, Monash University, Melbourne, Australia. [4] FuturES Research Center, Leuphana Universität Lüneburg, 21335 Lüneburg. Germany. [5] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK. [6] The Food and Environment Research Agency, Department for Environment, Food and Rural Affairs, H.M. Government, London SW1P 3JR, UK. [7] Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft, Suffolk NR33 0HT, UK. [8] UNE Business School, University of New England, Armidale, New South Wales 2351, Australia. [9] Centre for Environmental Management (CEM), School of Geography, University of Nottingham, Nottingham NG7 2RD, UK. [10] British Trust for Ornithology, Thetford, Norfolk IP24 2PU, UK. [11] Department of Land Economy, University of Cambridge, Cambridge CB3 9EP, UK. [12] Basque Centre for Climate Change (BC3) and IKERBASQUE, Basque Foundation for Science, 48011 Bilbao Bizkaia, Spain. [13] School of Geosciences, University of Edinburgh, Edinburgh EH9 3JW, UK. [14] School of Business, Economics and Social Sciences, University of Hamburg, Welckerstrasse 8, 20354 Hamburg, Germany. [15] Department of Spatial Economics and Institute for Environmental Studies (IVM), VU University Amsterdam, 1081 HV Amsterdam, and Department of Economics, Tilburg University, 5037 AB Tilburg, Netherlands. [16] Department of Environmental Science, Aarhus University, 8000 Aarhus, Denmark.

*Corresponding author. E-mail: i.bateman@uea.ac.uk

to economic analyses that assess the value of both marketed and nonmarketed goods (Table 1).

The NEA specifically addressed the consequences of land-use change driven by either agricultural values only or a wider set of values, all within the context of ongoing climate change. To assess this, raw data on land use and its determinants were drawn from multiple sources to compile a 40-year data set, spatially disaggregated at a resolution of 2-km grid squares (400 ha) or finer across all of Great Britain, forming more than one-half million sets of spatially referenced, time-specific, land-use records. Data on the determinants of that land use were assembled from multiple sources and included the physical environment (both spatially variable factors, such as soil characteristics and slope, and spatio-temporal climate variables, such as growing season temperature and precipitation); policy (both agricultural and relevant environmental measures, including subsidies, taxes, and activity constraints); market forces (such as prices and costs); and technology (reflected as changes in costs).

Land-Use Change

Land use in the United Kingdom is dominated by agriculture, which accounts for some 18.3 million hectares or 74.8% of the total surface area (*14*) and includes not only cropland but also the majority of grassland, mountain, moor, and heathland habitats. Agricultural land use was analyzed by using integrated environmental-economic models developed to capture spatial and temporal variation in determinants (*15*). These models start from the premise that farmers seek to arrange land use so as to maximize long-run profit, subject to the physical-environmental, policy, and price conditions they face in a given location and time (*13*). Even within the relatively small area of Great Britain, variation in environmental conditions is sufficient to yield very substantial differences in agricultural productivity and, hence, land use. These differences are captured by the model along with the variation due to other drivers; the models are verified by using rigorous out-of-sample, actual-versus-predicted, testing (*13*).

The focus of the analysis concerned the consequences of alternative land-use futures up until 2060. To assess this, information was needed regarding how drivers of land-use change might alter over that period. Some physical environment factors can be treated as fixed (for example, soil type) but others, most notably climate change, vary temporally and spatially. For these, modeled outputs of variables—such as growing season temperatures and precipitation (*16*)—were included in our land-use models. Certain market drivers were kept constant because of extreme uncertainties; for example, food prices may well rise because of increased demand from higher population and other pressures, but this may be mitigated by technological advance and behavioral change. Policy-induced changes—such as the consequences of stronger or weaker environmental regulation on both agricultural and other land—were addressed through an expert-based, deliberative process consistent with the Millennium Ecosystem Assessment (*1*). This process generated six plausible future scenarios, each described in terms of changes in regulations; these were either generally applied or spatially focused (Table 2). A rule-based approach was used to generate probabilities for each land-cover transition in each cell under each scenario [for example, transfers of land out of intensive agriculture to support the enhancement of areas of conservation importance, as per (*17*, *18*)]. Resultant scenarios are summarized in Table 2 and discussed in detail in (*13*).

Response of Market-Priced Goods to Land-Use Change

An initial analysis demonstrates the outcome of conventional land-use decision-making, which emphasizes market values (for example, agricultural produce) and ignores nonmarket ecosystem services. Maps of the change in the market value of agricultural output from the present day (2010 baseline) to 2060 under alternative climate change and policy scenarios (ignoring any effects from inflation) are shown in Fig. 1. In the first scenario (Fig. 1A), low emissions from greenhouse gases (GHGs) cause little climate change [taken from (*16*)] and have relatively little impact on farming during this period. However, relatively stronger environmental regulations are imposed (the NW scenario from Table 2) that restrict high-intensity farming in many areas, which results in declines in market agricultural values across much of the country. These relatively strong environmental regulations are maintained in the next scenario (Fig. 1B), but climate change now follows a high-emissions path. Although climate change is expected to have mixed consequences for agriculture at a global scale (*18*, *19*), comparison of Fig. 1A and 1B shows that farming in the United Kingdom will largely benefit from warmer temperatures. When the high-emission assumption is maintained (Fig. 1C), it weakens environmental regulations (the WM scenario). This allows land-use changes such as the conversion of some currently protected conservation areas into higher-intensity farming, which results in substantial further increases in agricultural production and corresponding market values.

In these scenarios, irrespective of climate change projections, if land-use decisions are based on market-priced goods alone, then a reduction in environmental regulations must always appear justified. Land-use change, however, alters not only market-priced agricultural outputs but many other important (but typically nonmarket) ecosystem services as well.

Response of Nonmarket Ecosystem Services to Land-Use Change

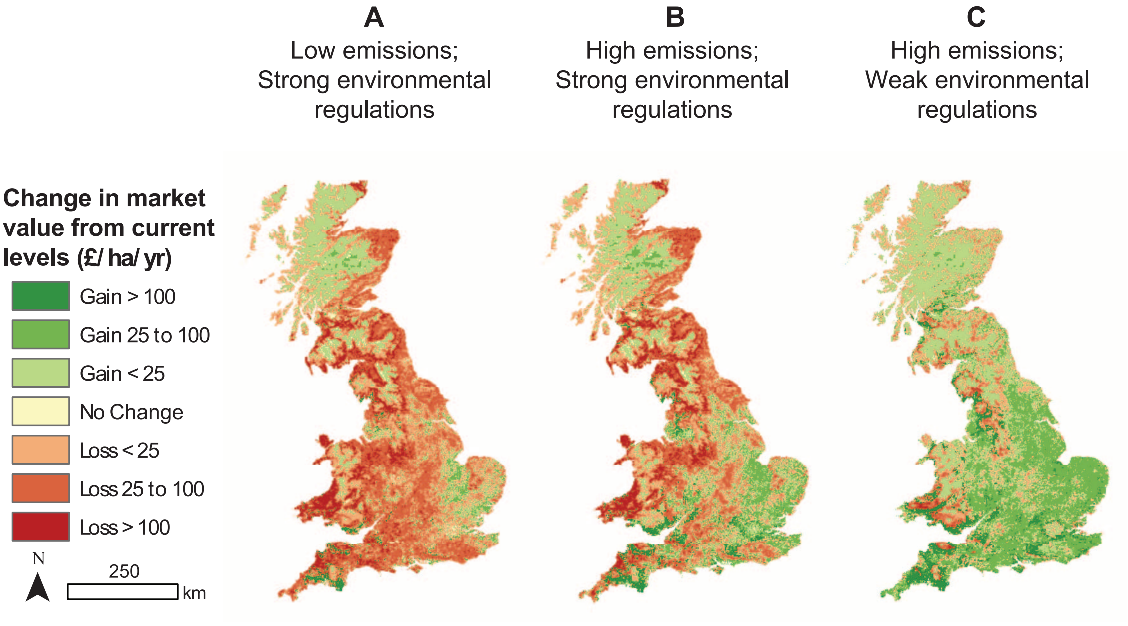
The analysis was extended to include the consequences of land-use change for GHG balance, open-access recreation, urban green space, and wild-species diversity [each modeled according to Table 1 and (*13*)]. Economic values were estimated for each of these additional impacts, with the exception of wild-species diversity, which is difficult to measure accurately using standard economic tools (*15*) and was accordingly assessed using a diversity index (*13*, *20*).

Land-use change was then modeled for all scenarios, by embracing a variety of combinations of environmental regulation and climate change, with

Table 2. Summary of land-use change scenarios. [Details in (*13*).]

Scenario	Environmental regulation and planning policy relative to current	Spatial focusing of changes
Go with the flow (GF)	**Similar:** Policy and regulatory regime as today. Existing patterns of countryside protection relaxed only where economic priorities dominate.	**Unfocused:** Similar spatial constraints on land-use change as today. No expansion of the protected area network.
Nature at work (NW)	**Stronger:** Policy and planning emphasize multifunctional landscapes and the need to maintain ecosystem function.	**Focused:** Greening of urban and peri-urban areas to enhance recreation values.
Green and pleasant land (GPL)	**Stronger:** Agri-environmental schemes strengthened with expansion of stewardship and conservation areas.	**Focused:** Increased extent of existing conservation areas. Creation of functional ecological networks where possible.
Local stewardship (LS)	**Stronger:** Agri-environmental schemes strengthened with expansion of stewardship and conservation areas.	**Unfocused:** No strong spatial component to changes but protection of areas of national significance continues.
National security (NS)	**Weaker:** Emphasis on increasing UK agricultural production. Environmental regulation and policy is weakened.	**Unfocused:** Some land-use conversion into woodland occurs in areas of lower agricultural values
World markets (WM)	**Weaker:** Environmental regulation and policy are weakened unless they coincide with improved agricultural production.	**Focused:** Losses of greenbelt to urban development, which results in loss of recreational values. Weaker protection of designated sites and habitats.

Fig. 1. Change from 2010 to 2060 in the market value of United Kingdom agricultural production under various climate and policy scenarios. (**A**) Under low-emissions climate projections [from (*16*)] and strong environmental regulations (NW scenario further described in Table 1), environmentally important habitats are conserved and farm intensification is restricted. (**B**) Under high-emissions climate projections (*16*) with the policy scenario as in (A). (**C**) Emissions as in (B) but with weak environmental regulations (WM scenario see Table 1). All values are adjusted for inflation.



the consequences assessed for all market and nonmarket ecosystem services (including agricultural outputs) and their value or indices. Changes in value from the 2010 baseline are shown in Fig. 2 under either the weaker environmental regulations of the WM scenario (top row of Fig. 2) or the stronger regulations of the NW scenario (bottom row); high-emission climate change projections were assumed in both cases. Considering agricultural values alone, results are (as per Fig. 1, B and C) that the weaker environmental regulations of the WM scenario yield higher market values. However, the nonmarket impacts of land-use change illustrated in the rest of Fig. 2 show that, across much of the country, strong environmental policies yield gains in the value of ecosystem services resulting from reduced GHG emissions and enhanced recreation and urban green space, as well as improvements in species diversity. Temporarily setting aside the nonmonetary wild bird–diversity index and summing across all other values shows that weaker (or stronger) environmental regulations lead to net losses (or gains) nationally; a result that reverses the restricted, market value assessment of Fig. 1. It is clear that considering market prices alone can drive decisions for land use that would deprive society of many other benefits from the environment and would risk leaving the United Kingdom worse, rather than better, off.

Benefits of Spatially Targeted Land-Use Planning

Whereas the two alternative futures shown in Fig. 2 illustrate the importance of bringing ecosystem services into decision-making rather than simply relying on market values, these extremes ignore the potential gains from working with the spatial and temporal heterogeneity of the natural environment and the underpinning biophysical processes. This variation makes it unlikely that any single policy will be optimal everywhere (for example, in Fig. 2 the generally superior NW policy still yields higher GHG emissions in northwestern Britain than the generally inferior WM scenario), which suggests, instead, that a move toward a spatially differentiated, targeted approach to decision-making will almost inevitably be better.

In order to examine the benefits of spatially explicit decision-making, the outcomes of each scenario were evaluated in each 2-km grid square across Great Britain, and the scenario that maximized a given objective in that cell was identified (Fig. 3). Results showed that, although a conventional, market-dominated approach to decision-making chooses options to maximize agricultural values (Fig. 3A), these policies will reduce overall values (including those from other ecosystem services) from the landscape in many parts of the country (Fig. 3B); notably in upland areas (where agricultural intensification results in substantial net emissions of GHG) and around major cities (where losses of greenbelt land lower recreation values). In comparison, an approach that considers all of those ecosystem services for which robust economic values can be estimated (Fig. 3C) yields net benefits in almost all areas, with the largest gains in areas of high population (Fig. 3D).

To provide an idea of the scale of potential gains, consider that our measure of agricultural profitability [technically, farm gross margins (*21*)] suggests returns to farming (including subsidies) ranging from £400/ha to in excess of £1000/ha, depending on location [see (*22*)]. Our analyses suggest that a targeted approach to land-use planning that recognizes both market goods and nonmarket ecosystem services would increase the net value of land to society by 20% on average, with considerably higher increases arising in certain locations.

Decisions based on all ecosystem services for which robust economic values can be derived (Fig. 3, C and D) are clearly better than those based only on a conventional pursuit of market priced goods (Fig. 3, A and B). However, this analysis omits impacts that cannot be reliably monetized, for example, the effects on wild bird species diversity. We now incorporate our measures of change in wild bird species diversity through the application of a simple constraint requiring that, in each area, any policy that resulted in a reduction in the species-diversity index was ruled out for that area (Fig. 3, E and F). The similarity to Fig. 3, C and D, shows that, when applied in a targeted manner, this constraint has relatively little impact upon which scenario is best; that is, the "opportunity cost" (*17*) of imposing a species conservation constraint is relatively minor. Nevertheless, comparison of Fig. 3, C and E, shows that, in certain areas, the sustainability constraint causes a shift from scenario NW, which focuses on the enhancement of greenbelt areas for recreation, to scenario GPL, which focuses on extension of existing areas of conservation value.

National-Scale Implications

Monetary sums from the analyses of Fig. 3 are shown in Table 3. Even if we only consider agricultural market values, then a targeted approach to maximizing these values (first column of results) can yield a small gain in total values relative to the present situation (a result that is not feasible using single policies applied over all of the country, which highlights the inefficiency of current one-size-fits-all policies, even when they are only assessed in terms of market value). However, a targeted approach to optimizing both market and nonmarket values yields a major increase in gains (second column of results). Furthermore, placing a targeted biodiversity constraint on the latter approach only marginally reduces these gains (final column), which suggests both that such constraints are a highly effective and efficient solution to conserving wild-species diversity and that land-use policies that increase GHG storage and recreation values typically correlate with improvements in such diversity.

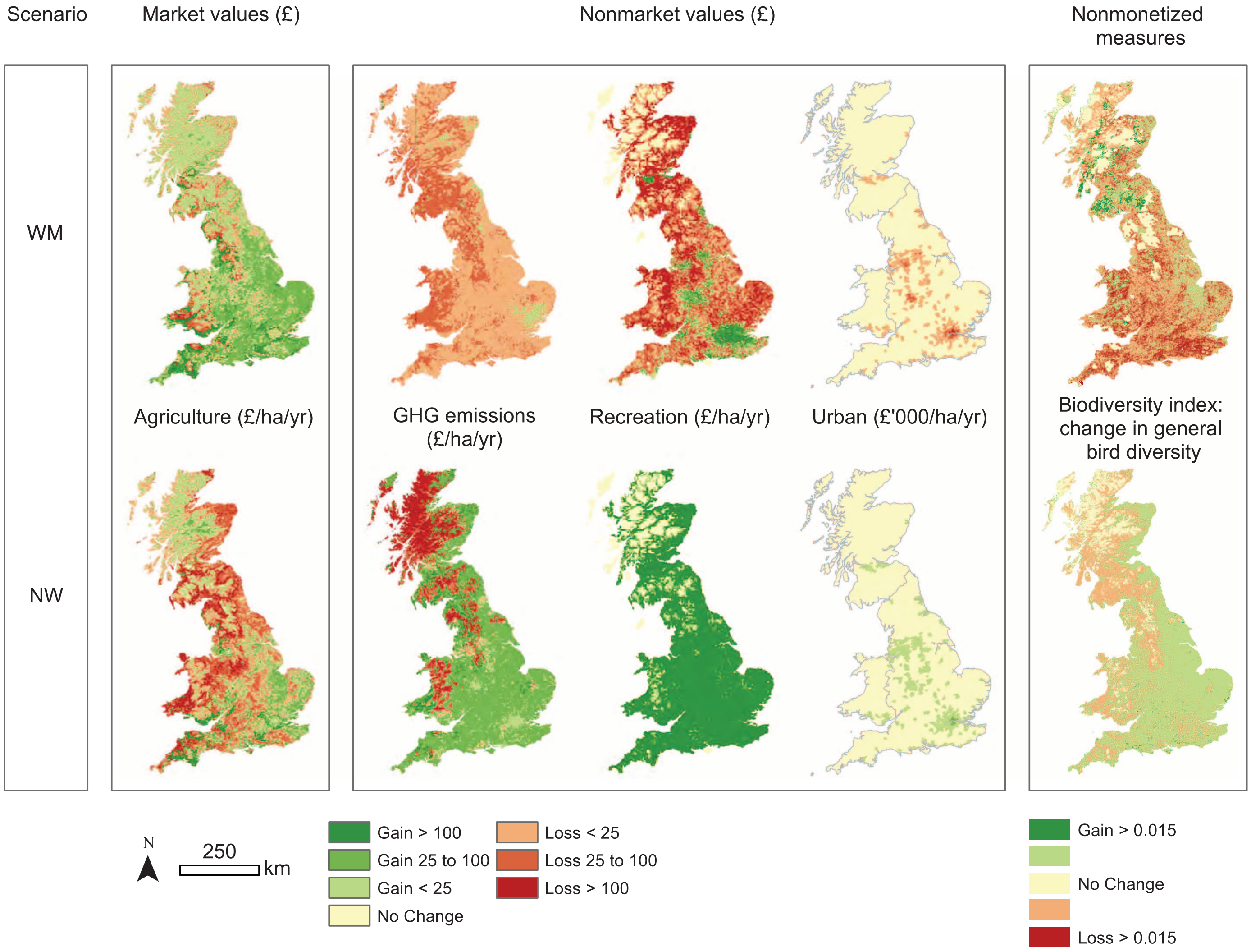


Fig. 2. Spatial distribution of the changes in market and nonmarket ecosystem service economic values and nonmonetary wild species–diversity assessments. These were measured as changes in Simpson's Diversity Index (*13*, *20*) induced by moving from the year 2010 baseline to the WM and NW scenarios for 2060 [all analyses assume high GHG emission climate-change projections from (*16*)] (*30*).

Recreation values arising from these changes exceed those from agriculture (Table 3). This striking difference does not imply that the total value of recreation is greater than that of food. It comes about because economic analyses such as this evaluate alternatives by focusing not on total values but on the changes in value that these alternatives generate. In a highly developed country such as the United Kingdom, where food is plentiful and cheap but opportunities for recreational use of the natural environment are somewhat limited, it is not surprising that converting some comparatively small amount of land out of agriculture and into open-access recreation yields a relatively modest loss in farm produce value while at the same time generating a much bigger value from increased recreation. This positive disparity will be greater if (as in this analysis) such conversions are spatially targeted so as to maximize net benefits (here, by ensuring such land-use conversions occur near urban centers where resulting recreational gains can be huge). However, as progressively more land is converted to recreation, the number of additional visits generated will fall, whereas the agricultural loss of each conversion steadily mounts (explaining why only a limited area, typically near to cities, is converted to recreation). Obviously, such results would vary substantially if analyses were conducted in very different contexts, such as in less developed countries where the value of changes in food may be much higher relative to those for recreation.

From Potential to Practice

Our analysis shows that land-use decisions based on market prices alone can reduce the overall value of the sum of agricultural and monetizable ecosystem services at the national scale. Although the economic values provided in Table 3 are subject to certain assumptions (*13*), further work to elaborate significant underpinning processes—such as the effects of ecological, biodiversity, and other global change factors (*23*–*25*)—and to better reflect links between economic valuation of ecosystem services and decisions seem unlikely to alter this general conclusion. Indeed, if other services such as water resources were added to the analysis, current national estimates of pollution costs (*26*) imply that the differences would be accentuated.

Although potential improvements in land-use planning would generate social gains sufficient to more than compensate for any associated losses, a new direction for land-use decision-making does not come without implementation challenges. A first challenge concerns the mechanics of securing the participation of land managers in delivering land-use changes that are unlikely to be privately beneficial. In the United Kingdom, the obvious mechanism through which that goal could be achieved is reform of the European Union's (EU's) Common Agricultural Policy (CAP). Currently, CAP payments to UK farmers are in excess of £3 billion per annum (*27*) compared with a total value of UK agriculture of only £5 billion per annum (*28*) with the vast majority of those payments (70%) made without consideration of

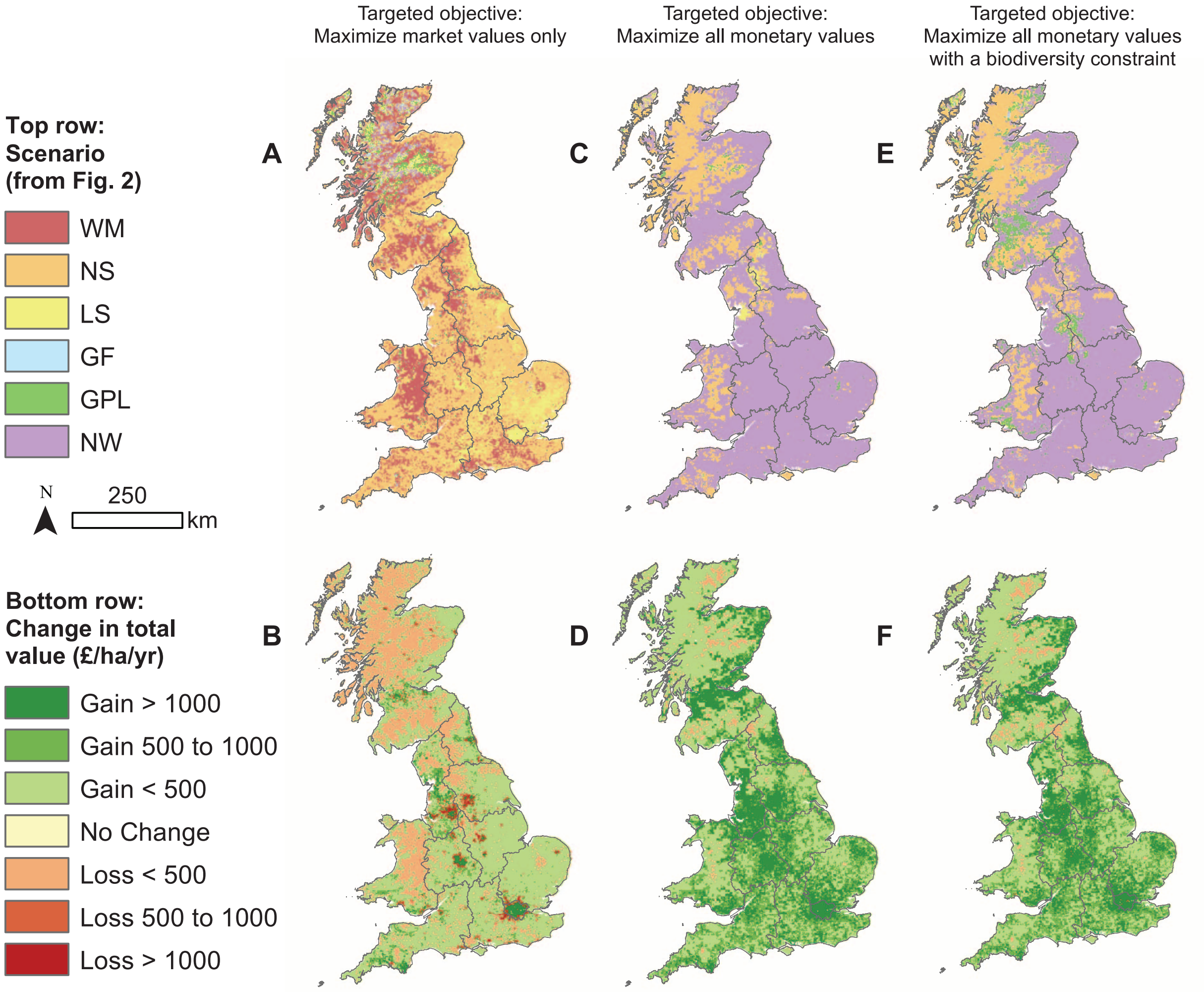


Fig. 3. Optimal scenarios and changes in value. Optimal scenarios (**A**, **C**, and **E**) for each 2-km grid square and corresponding changes in value from 2010 to 2060 (**B**, **D**, and **F**) in Great Britain under three alternative targeted objectives: (i) conventional approach maximizing market values only (A and B); (ii) maximizing the value of all those ecosystem services that can be robustly monetized (C and D); (iii) maximizing all ecosystem service values but with a constraint so that no scenario that gives a net loss of wild bird diversity is permitted in the area affected (E and F) [all analyses assume low GHG emissions, climate change from (*16*)] (*30*).

Table 3. Change in values across Great Britain from the present day (2010) to 2060 achieved by the targeting of policy options under three decision rules. (Millions of £s per annum; real values in £2010; UK Climate Impacts Programme low-emission scenario throughout.)

Decision component	Maximize market (agricultural) values only (Fig. 3, A and B)	Maximize all monetary values (Fig. 3, C and D)	Maximize all monetary values with biodiversity constraint (Fig. 3, E and F)
Market agricultural value	971	−448	−455
Nonmarket GHG emissions	−109	1,517	1,510
Nonmarket recreation	2,550	13,854	12,685
Nonmarket urban green space	−2,520	4,683	4,352
All monetary values	892	19,606	18,092

environmental performance. Recasting the CAP as a Payment for Ecosystem Services (PES) mechanism, such that farmers are rewarded for the delivery of a broad spectrum of ecosystem services, would provide policy-makers with a very powerful tool through which to secure beneficial land-use change.

A second challenge arises from the need, clearly demonstrated in this research, for that mechanism to allow for spatial targeting, a prescription that stands in sharp contrast to the spatial insensitivity of current CAP payment allocation. Spatial targeting, however, necessarily increases pressures upon decision-making and administrative institutions. The key challenge, therefore, is to realize the gains from spatial targeting without overly inflating the costs of policy implementation.

A final challenge concerns how to efficiently target payments when the costs of delivering ecosystem services differ across land managers but are unknown to the funding authority. To that end, recent developments in the design of PES mechanisms suggest that competitive contracting may deliver considerable efficiency gains (*29*).

Principles for Future Land-Use Analysis and Planning

Our results allow us to refine the following principles for future analyses and decision-making: (i) The conventional focus upon market-priced goods alone can result in decisions that lower overall values; (ii) all the major ecosystem services generated by a change in resource use need to be assessed; (iii) that assessment must recognize spatial and temporal variation in ecosystem services, as well as synergistic impacts such as those arising between climate and land-use change; (iv) changes in ecosystem service flows should be valued wherever robust economic values are available; (v) difficult-to-monetize impacts, such as those on wild species, should be incorporated through the imposition of sustainability constraints, which can then be satisfied in cost-effective ways; (vi) spatial targeting of policies can generate major gains; and, perhaps most important, (vii) a range of substantial benefits to society can be realized by bringing natural science and economic information together to inform environmental decision-making. Taken together, we hope that these principles and their demonstration through the case study illustrate the practical potential for national, yet spatially sensitive, application of an approach to decision-making that places ecosystem services on a level playing field with market-priced goods and, thereby, contributes to the sustainable use of Earth's limited resources.

References and Notes

1. Millennium Ecosystem Assessment, *Ecosystems and Human Well-Being: Synthesis* (Island Press, Washington, DC, 2005).
2. A. Balmford *et al.*, *Science* **297**, 950–953 (2002).
3. H. Tallis, A. Guerry, G. C. Daily, in *Encyclopedia of Biodiversity*, S. A. Levin, Ed. (Academic Press, Waltham, ed. 2, 2013), pp. 96–104.
4. E. B. Barbier *et al.*, *Science* **319**, 321–323 (2008).
5. J. A. Foley *et al.*, *Nature* **478**, 337–342 (2011).
6. R. Naidoo, T. H. Ricketts, *PLoS Biol.* **4**, e360 (2006).
7. E. Nelson *et al.*, *Front. Ecol. Environ* **7**, 4–11 (2009).
8. J. H. Goldstein *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 7565–7570 (2012).
9. S. Polasky, E. Nelson, D. Pennington, K. A. Johnson, *Environ. Resour. Econ.* **48**, 219–242 (2011).
10. J. A. Foley *et al.*, *Science* **309**, 570–574 (2005).
11. D. Schröter *et al.*, *Science* **310**, 1333–1337 (2005).
12. NEA, *UK National Ecosystem Assessment: Technical Report* [United Nations Environmental Programme–World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, 2011].
13. Supplementary materials are available on *Science* Online.
14. Department for Environment, Food, and Rural Affairs (Defra) (United Kingdom); Department of Agriculture and Rural Development (Northern Ireland); The Department for Rural Affairs and Heritage, Welsh Assembly Government; Rural and Environment Research and Analysis Directorate, The Scottish Government, *Agriculture in the United Kingdom 2011* (Office for National Statistics, Newport, UK, 2011).
15. I. J. Bateman, G. M. Mace, C. Fezzi, G. Atkinson K. Turner, *Environ. Resour. Econ.* **48**, 177–218 (2011).
16. G. J. Jenkins *et al.*, *UK Climate Projection: Briefing Report* (Met Office Hadley Centre, Exeter, UK, 2009).
17. J. H. Lawton *et al.*, "Making space for nature: A review of England's wildlife sites and ecological network: Report to Defra" (Defra, London, 2010).
18. D. B. Lobell, W. Schlenker, J. Costa-Roberts, *Science* **333**, 616–620 (2011).
19. J. Schmidhuber, F. N. Tubiello, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 19703–19708 (2007).
20. E. H. Simpson, *Nature* **163**, 688 (1949).
21. C. Fezzi, D. Rigby, I. J. Bateman, D. Hadley, P. Posen, *Agric. Econ.* **39**, 197–205 (2008).
22. I. J. Bateman, A. A. Lovett, J. S. Brainard, *Applied Environmental Economics: A GIS Approach to Cost-Benefit Analysis* (Cambridge Univ. Press, Cambridge, 2003).
23. A. D. Barnosky *et al.*, *Nature* **486**, 52–58 (2012).
24. B. J. Cardinale *et al.*, *Nature* **486**, 59–67 (2012).
25. A. P. Kinzig *et al.*, *Science* **334**, 603–604 (2011).
26. A. Moxey, "Agriculture and water quality: Monetary costs and benefits across OECD countries" (OECD, Paris, 2012).
27. Defra, CAP payments (Defra, London, 2013); www.cap-payments.defra.gov.uk/Default.aspx.
28. U.K. Agriculture, Economic trends (Living Countryside, Peterfield, UK, 2013); www.ukagriculture.com/farming_today/economic_trends.cfm.
29. P. J. Ferraro, *Ecol. Econ.* **65**, 810–821 (2008).
30. Ordnance Survey data, Crown copyright and database right 2013.
31. Department for Environment Food and Rural Affairs, "June agricultural census" (Edina, Manchester, 2010).
32. Ordnance Survey, "Land-Form PANORAMA (Digital Elevation Model)" (OS OpenData, Southampton, 2010); www.ordnancesurvey.co.uk/oswebsite/products/os-opendata.html.
33. M. Van Liedekerke, P. Panagos, ESDBv2 Raster Archive (European Commission and the European Soil Bureau Network, Brussels, 2005).
34. C. Fezzi, I. J. Bateman, *Am. J. Agric. Econ.* **93**, 1168–1188 (2011).
35. C. Fezzi *et al.*, *Agric. Econ.* **41**, 123–134 (2010).
36. R. Lal, *Environ. Int.* **30**, 981–990 (2004).
37. A. R. Mosier *et al.*, *Clim. Change* **40**, 39–80 (1998).
38. P. Smith *et al.*, *Agric. Ecosyst. Environ.* **118**, 6–28 (2007).
39. Department of Energy and Climate Change, "Guidance on estimating carbon values beyond 2050: An interim approach" (Department of Energy and Climate Change, London, 2009).
40. Natural England, "Monitor of engagement with the natural environment" (Technical Report NECR050, Natural England, London, 2010).
41. Casweb, "UK Census" (UK Data Service Census Support, Mimas, 2001); http://casweb.mimas.ac.uk/.
42. K. Risely *et al.*, *The Breeding Bird Survey 2011* (BTO Research Report 624, British Trust for Ornithology, Thetford, UK, 2011).

Acknowledgments: This work was funded by The UK-NEA and its Follow-On program [which are together supported by the UK Defra; the devolved administrations of Scotland, Wales, and Northern Ireland; the Natural Environment Research Council (NERC) and the Economic and Social Research Council (ESRC)]; and the Social and Environmental Economic Research (SEER) project (ESRC Funder Ref: RES-060-25-0063). I.J.B. led the project with support from all authors; the analysis was designed by I.J.B., A.R.H., G.M.M., and R.W.; C.F., I.J.B., U.P., D.H., P.M., A.R.H., and A.S. undertook the farm land–use analysis; D.J.A., U.P., M.T., C.F., and I.J.B. undertook the GHG analysis; A.S., A.R.H., I.J.B., A.C., J.F., and P.M. undertook the recreation analysis; G.P., B.A., A.K., and I.J.B. undertook the urban green space analysis; M.H., G.S., S.D., and A.A.L. undertook the biodiversity analysis; R.H.-Y. and J.P. undertook the scenario-building exercise; A.R.H. undertook the synthesis and targeting analysis with I.J.B., G.M.M., A.B., B.H.D., and D.v.S.; I.J.B., A.R.H., and G.M.M. wrote the paper with contributions from all authors. We are grateful to P. Dasgupta and K.-G. Mäler for research advice. We declare no conflict of interest. Data are included in the supplementary materials available on *Science* Online.

Supplementary Materials

www.sciencemag.org/cgi/content/full/341/6141/45/DC1
Supplementary Text
Figs. S1 and S2
Tables S1 to S15
References (*43*–*132*)
Data Table S1

20 December 2012; accepted 20 May 2013
10.1126/science.1234379

REPORTS

Signatures of Cool Gas Fueling a Star-Forming Galaxy at Redshift 2.3

N. Bouché,[1,2]* M. T. Murphy,[3] G. G. Kacprzak,[3] C. Péroux,[4] T. Contini,[1,2] C. L. Martin,[5] M. Dessauges-Zavadsky[6]

Galaxies are thought to be fed by the continuous accretion of intergalactic gas, but direct observational evidence has been elusive. The accreted gas is expected to orbit about the galaxy's halo, delivering not just fuel for star formation but also angular momentum to the galaxy, leading to distinct kinematic signatures. We report observations showing these distinct signatures near a typical distant star-forming galaxy, where the gas is detected using a background quasar passing 26 kiloparsecs from the host. Our observations indicate that gas accretion plays a major role in galaxy growth because the estimated accretion rate is comparable to the star-formation rate.

At all epochs, galaxies have short gas depletion time scales (*1*, *2*); to sustain the observed levels of star formation over many billions of years, galaxies must continuously replenish their gas reservoir with fresh gas accreted from the vast amounts available in the intergalactic medium. In numerical cosmological simulations (*3*–*5*), the accretion phenomenon is often referred to as "cold accretion" (*6*), and this term describes the mass regime where the accretion is most efficient (*7*, *8*). The cold accreted gas should orbit about the halo before falling in to build the central disk, delivering fuel for star formation and also angular momentum to shape the outer parts of the galaxy (*9*, *10*). Thus, accreting

---

[1] CNRS/IRAP, 14 Avenue E. Belin, F-31400 Toulouse, France. [2] Université de Toulouse/UPS-OMP/IRAP, F-31400 Toulouse, France. [3] Swinburne University of Technology, P.O. Box 218, Hawthorn, Victoria 3122, Australia. [4] Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388 Marseille, France. [5] Department of Physics, University of California, Santa Barbara, CA 93106, USA. [6] Observatory of Geneva, 51 Chemin des Maillettes, CH-1290 Versoix, Switzerland.

*Corresponding author. E-mail: nicolas.bouche@irap.omp.eu