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Designing sustainable landuse in a 1.5 °C world: the complexities of projecting multiple ecosystem services from land

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Land provides a range of critical services for humanity (including the provision of food, water and energy). It also provides many services that are often *socially* valuable but may not have a *market* value. Demand projections for land-based services, accounting for the significant requirement for negative emissions needed to meet a 1.5 °C pathway, may exceed what can be sustainably supplied. It is therefore critical to explore how to optimise land use (and if necessary, limit demand), so societies can continue to benefit from all services into the future. Unlike the energy or the transport sectors, however, there is limited understanding or consensus over what 'optimal' land use might look like (from a science perspective), or how to bring it about (from a governance perspective).

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Introduction: land is finite, demand may not be

Land provides a range of important ecosystem services vital for human health and wellbeing: food; energy; water; carbon storage; habitats for biodiversity; space for recreation, amenity and living; and cultural services. Currently, 4.9bn ha of global land is used for agriculture (about 38% of total land area)[4]; a further 4.0bn ha (31%) is forested, of which 290 m ha is planted (FAOSTAT, 2017).[5]

Whilst the amount of land is largely fixed, demand for the services from land is projected to rise under business-as-usual scenarios, driven by economic and population growth:

- Marketed energy is projected to increase by 48% between 2012 and 2040 [1];
- Water demand is projected to increase by 100% by 2100, this on top of current consumption levels of $\sim$2000 km^{-3} yr^{-1} of water and despite the fact that 4bn people today experience some degree of annual water scarcity [2,3];
- Food supply may need to increase by 60% by 2050, according to FAO projections [4]. As crop yields are not currently growing at the same pace as demand [5] this implies an expansion of agricultural land area [6••]. Although estimates vary, depending on assumptions made and modelling frameworks, most models agree cropland is likely to expand by 10–26% [7]. In the extreme, without further innovation beyond current yield trends, to meet currently projected demand, cropland would increase by 42% and pasture by 15% [6••].

At the same time as demand is growing for services from land, agricultural land is being lost to urban and infrastructural expansion and to sea-level rise. In Europe alone, between 70 and 75 kha of 'land-take' occurred between 1990 and 2006 [8]. On a global basis, by 2030, urban expansion may have taken land that, in 2000, produced 3–4% of global crop yields [9]. Furthermore, rising sea levels risk both a reduction in available agricultural land in coastal areas and a consequent increase in competition for resources inland as coastal populations are forced to migrate [10•].

On top of this, meeting climate goals — and in particular limiting global warming to 1.5 °C by 2100 — will intensify demand on land for energy and carbon storage. The 1.5 °C target implies a very tight carbon budget that is

[4] Based on 2014 data.
[5] http://www.fao.org/faostat/en/#data/RL.

likely to be exhausted in the next few years, necessitating deployment of negative emissions technologies (NETs) at scale to offset excess emissions [11••]. The IEA's 2016 World Energy Outlook [12] indicates that, if net-zero emissions are not reached until 2060, a 1.5 °C degree pathway may require up to 800 Mha of land for bioenergy with carbon capture and storage (BECCS) (see Fig. 8.16 in [10•]). This is equivalent to 56% of the world's arable land area.[6] Even for a 2 °C pathway, BECCs will likely require in the range of 380–700 Mha of land; an alternative NET strategy of afforestation and reforestation would require a comparably large area [11••].

In sum, the accumulated demands on land, as currently projected by the different sectors, may be incompatible. Although there is good knowledge of today's land use, there has been insufficient cross-sectoral analysis of how finite land resources can and should be apportioned between multiple services, either now or in the future. Existing projections of land demand are often mono-sectoral and lacking in nuance. For example, discussion of the potential cultivation of 'underutilised land' often fails to recognise that this land may already be populated, managed, and providing a range of less monetised services [13]; there is little 'spare land' [14•].

Furthermore, in the absence of well-evidenced indicators of the limits to sustainable production and how these vary between places, it is difficult to understand the potential upper limits of intensification, either at the level of planetary [15••] or local boundaries. Surpassing such limits would have wider implications: failure to manage soils sustainability will, for example, increase competition for land [16] if it leads to lower yields and land abandonment [17•].

A key need is for greater attention to be paid to investigating how best to manage land, sustainably, in order to derive the mix of services that societies globally, and locally, require.

Are our land resources enough to meet our demand?

Despite the obvious constraints on the extent and capacity of global land, there is an implicit assumption that our 'land bank' can — and will continue to — meet our demands for services. When expected demand across services is aggregated, however, it may far exceed what is 'in the bank', especially under a 1.5 °C pathway that depends on significant land-resources for NETS.

This raises three major questions.

1) **To what extent can technology increase the service delivery capacity of land?** There is significant optimism that development and deployment of new technologies, and wider adoption of existing technologies, will improve yields of services (per unit area). However, the extent to which technologically-driven productivity growth is realisable is less clear, as are its limitations and social acceptability.
2) **How can we make optimal use of our land?** Assuming there are finite limits to the service-delivery capacity of a parcel of land, it will be necessary to identify or create decision-support tools that help us make the most of the land available.
3) **Will land services fall short of demand?** Through the process of land use optimisation, which service demands will not be met? How will the shortfall in capacity differ between geographies and among actors? How could demand, therefore, be modified?

Of these three questions, the first has been the focus of significant attention over the years (and we address it briefly below). The third, is increasingly a focus of attention, especially in the light of planetary boundaries' discussions (and we return to it later). The second question deserves more attention, and is the focus of this paper.

Can technology deliver greater service provision?

The role of technology in improving outputs whilst reducing the environmental costs of production has been examined and discussed extensively in the food security arena as 'sustainable intensification' [18•,19]. Whilst there is clear agreement that agricultural productivity growth has arisen from innovation, it has led to extensive external costs in terms of environmental degradation, emissions, waste generation and healthcare costs.

Whilst production and efficiency gains are certainly possible for services like food [20], water use and energy production and may improve some aspects of external environmental costs, the degree to which agricultural yields can grow *sustainably* remains contested [19,21]. For example, efficiency gains may spill-over to greater productivity and increase environmental impact [22] or farming technologies may improve yields, but higher yields may require more inputs with environmental consequences, and may also come with reduced nutritional benefits [23]. There is growing recognition that technological 'silver bullets' often have complex unintended consequences, and are unlikely to offer the sole solution to grand challenges [24,25•]. Therefore, in addition to productivity growth from each parcel of land, it will be necessary to get smarter about how we use land to optimise service provision.

The challenging science of optimising land-use

Leaving aside the governance challenges of how a 1.5 °C pathway might be implemented, the science based

[6] Based on 2014 data.

challenge is this: is it possible to 'design' a sustainable land use strategy that, within the constraints of maintaining an appropriate, place-based mix of services, meets the global challenges embodied in the Paris agreement and the UN's Sustainable Development Goals? In order to do this, we would need to project service delivery from the land, under different scenarios of land use, in order to weigh-up the limits and sustainability of provision, and how it might map onto demand.

However, developing a comprehensive, data-based, approach to optimizing land use is problematic for a number of reasons. We highlight three broad challenges below.

Firstly, optimizing land use to balance competing service demands sustainably is technically a 'wicked problem': one for which there is no straightforward solution [26]. The same intervention may lead to different outcomes in different places, and, unlike most other dynamical systems, biological and ecological systems often respond unpredictably to interventions [27]. Divergent outcomes may also arise from differences in the way that ecosystem services are interconnected across space; or from human decision-making, an integral dimension of land management often affected by multiple conflicting drivers [28].

Secondly, land management inevitably implies trade-offs of some kind — between services, among actors, and between short-term and long-term costs and benefits. A given intervention may enhance one service at the expense of another; for example, increasing the intensity of farming to boost food outputs may impact negatively on the availability or quality of water [29••]. Furthermore, changing farming practice, for example, can often benefit the biodiversity of certain species groups while harming that of others [30].

Such trade-offs have implications for service delivery, and clearly also affect land-use governance by impacting on the differing actors that may value the services. For example, boosting yields may create private goods for the farmer, but decrease public goods that have monitized value (e.g. water supply) or non-monitized value (e.g. biodiversity) for the population as a whole. Trade-offs necessitate that we optimise across services, rather than maximise each one independently, to avoid one actor creating benefit at the expense of others' loss.

However, optimising across trade-offs creates other governance challenges: for whose benefit is any optimisation conducted? Who decides the weighting between, say, food and clean air? Existing policy-based and market-based solutions are often ill-equipped to manage this complexity [31,32]. Many suggest the need for significant institutional changes and reframing of land governance based on new, inclusive, principles [33,34], recognising that stakeholders in the services produced by a parcel of land may be global, national or local, as well as not yet born.

Thirdly, the impact of a given land intervention is highly context-dependent: impacts depend to a great extent on the place in which an intervention is adopted and the scale at which it is implemented. A range of factors can affect the outcome — not only local soil quality, climate and topography, but also the geographical and temporal scale of the intervention's implementation.

To illustrate this, in a recent analysis exploring the interrelationships between farming's impact on yields and other services [29••], 52 studies were found that measured the association between soil carbon and agricultural yield. On average, across the studies, yield was positively associated with soil carbon (a correlation of +0.73). However, individual studies showed the full range from perfect positive to perfect negative relationships (+1.0 to −1.0), with the middle 50% of all the studies ranging from strongly negative to strongly positive associations between soil carbon and yield (−0.65 to +1.0).

In addition to the place-dependence of a specific intervention, further complexity arises from the fact that an intervention's impact is likely to change non-linearly as it is implemented across time and space. An intervention may have different impacts depending on what practice neighbouring land-managers adopt, for example, either through scale-dependent bio-physical [30] or social/market effects [35,36]. 25 $g\ m^{-2}$ of synthetic fertiliser applied on a single square metre will have no noticeable ecological impact, but the same rate of fertiliser use across a whole landscape will impact significantly on soil, water, air quality and biodiversity. Equally, frequency-dependence means outcomes may change non-linearly with the proportion of actors adopting a particular intervention [37]. For example, in a large undisturbed area of natural land, the first 1% of land converted may not have noticeable impact on the services that land provides, but if 99% of the land is already converted, converting the final 1% will cause extinction of the remaining native biodiversity.

Thus, to define an optimal land-use strategy to deliver a range of services is more complex than simply assigning a landuse or land-management option to a parcel of land, as outputs vary with space, time, scale, neighbourhood composition; and trade-off locally, and in aggregate. We need to better recognise the trade-offs of the services, the nuances of spatial and temporal impacts, the detailed context-dependencies of place. These then need to be meshed with the interests of different constituencies of stakeholders. In other words there are deep, often unacknowledged, science and governance challenges associated with the transformation of the land-economy, perhaps much more complex than transforming the energy sector. Furthermore, as the market works across boundaries, changing land use in one place (such as producing less food but a greater level of other services) will send price signals to change outputs in other areas. Thus, optimising land use in a single place may create sub-optimal land use in another. To address the global goals requires global, as well as local, optimisation.

The sheer complexity of the challenge risks policy paralysis, particularly where the risk of unintended consequences is perceived to be too high — such as may be the case for the widespread deployment of land for NETS. Taking the case of NETS, the questions of what kind of land could be used, where that land is found, and what impacts its use might have on food availability, price, water and biodiversity are just beginning to be addressed [38].

Unlocking smarter land-use for a 1.5 °C pathway: the science research agenda

The data revolution, particularly advances in remote sensing, has made high-resolution data increasingly available across large areas [39]. Groups around the world have been developing algorithms to utilise these data for mapping multiple services (e.g. using distribution and connectivity of vegetation communities as a proxy for biodiversity) [39,40]. It is now feasible, at least in some geographies, to develop 'landscape simulators' able to model land-use at high resolution (<10 m) and the associated multiple ecosystem services [41,42]. Such modelling, that integrates across services, can be used to assess policy options, hence their name: integrated assessment models or IAMs.

Whilst there have been many attempts to manage multiple services from landscapes (e.g. [42]), trade-offs between services (e.g. [43••,44]), or assess the land available for agriculture and other uses (e.g. [13]), most integrated land-use assessments deal with the services arising from land in a superficial way [45], ignoring the challenges outlined above. In short, current modelling capabilities are not sophisticated enough to meet the full range of decision-makers' needs.

Furthermore, projecting into the future requires assumptions about how the world, and the demand for multiple services, may develop. Although important work exists on emissions trajectories describing 'Representative Concentration Pathways' (RCPs) [46] and Shared Socioeconomic Pathways (SSPs) that might drive them [47], a number of variables critical to demand for land-based services have received insufficient attention (including a Paris-compliant RCP for 1.5 °C). Other factors include the extent to which the increasingly burdensome healthcare costs associated with poor diet will trigger interventions to shift dietary preferences, and in turn how 'healthy, sustainable' consumption patterns may radically alter production systems and reduce systemic waste [48,49]. Additionally, including scenarios that illustrate how different demand trajectories affect competition for land-based services could help policy-makers balance supply-side and demand-side interventions.

A key challenge for decision-making in the context of such complexity is the need to ensure simultaneous modelling not only of different ecosystem services, but of different scales in such a way that captures the intimate connection between local actions and global drivers (Figure 1). Market integration means local land management decisions are often determined, at least in part, by outputs and prices elsewhere. For example, a national decision to mandate a 'sustainable' farming practice (such as organic farming) could benefit certain ecosystem services at local level but reduce national yields [50]. In the absence of a reduction in national demand, food imports would increase, driving the intensification or extensification of agriculture, and degradation of ecosystem services, elsewhere [51]. Whether an intervention is positive, and for whom, therefore depends on the scale not just of the intervention but also the analysis.

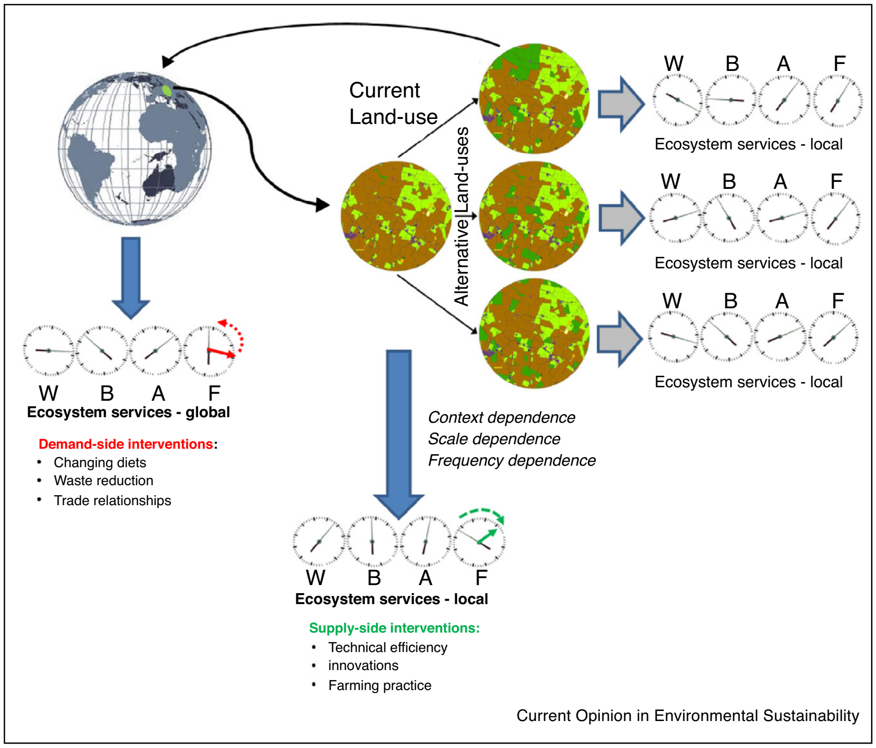
Consequently, an 'uber' integrated assessment modelling approach (uIAM) is required; IAMs that allow for the costs and benefits of an intervention at local scale to be balanced with those across the global market [52]. Such an approach could help policy-makers understand trade-offs between land-based services at different scales; anticipate and manage problematic outcomes; and quantify the scale and nature of required demand-side interventions.

In some sense, all models are wrong, but complex systems are beyond our cognitive ability to analyse without models, and complex models of complex systems are often needed in order to simulate their future states [53]. With climate models, the complexity (and realism) has increased over time (and continues to, see e.g. [54]), and an ensemble of models are used to reduce uncertainty due to model construction. Such models are highly complex, and highly useful, even with their limitations. The land economy is so important to planetary function, sustainable development and social well-being, that we should not avoid trying to develop suites of complex models in order to model its complexity.

Conclusions

Meeting climate change goals, whether for temperature stabilisation at 1.5 °C or 2 °C, will intensify competition for land-based services; quite probably beyond what can sustainably be delivered on current land in the absence of changes in consumption. Developing Paris-compliant land-use strategies will likely require balancing trade-offs between services and interventions to reduce demand. However, decision-making is hampered by problems of

Figure 1



A conceptual illustration of what would be required of an all-encompassing integrated assessment model 'uber IAM'. Global levels of ecosystem services are calculated from a spatially explicit model based on fine scale information, with land-use contextually translated into a range of ecosystem services. The multiple ecosystem services are represented by the dashboard of dials (with W: water, A: air quality, B: biodiversity, F: food). The estimation of services would be depend on **(a)** local capacity and **(b)** scale-dependence and frequency-dependence. The totality of ecosystem services at global and local levels would depend on technologies applied (e.g. yields, inputs, efficiencies = sustainable intensification), depicted by the green arrow on the local dial, and the patterns of land use, depicted by alternative land use scenarios. The totality of services required could be changed through demand-side interventions (e.g. systemic efficiency, behavioural changes in consumption patterns), depicted by the red arrow. By changing the parameters (e.g. technological efficiencies) and land use, such models could explore global provisioning capacities and whether they fit within local and planetary boundaries, and therefore aid local planning for optimal land use.

wickedness and scale-dependence that mean the outcomes of any intervention — for different services and different locations — are hard to predict.

In response, the academic community should prioritise the development of scalable integrated assessment models and use them as the analytical basis for holistic impact assessments capable of anticipating how different interventions may affect multiple services over space and time. Detailed local-to-global models could be used to delimit the maximum sustainable provision of all services, based on local capacities and aggregated to landscape, regional or global scales. The identification of these maximum provision levels would provide an evidential basis on which to counter the implicit assumption that current and projected demand for services can *and should* be met.

It is clear that land-use planning will require greater due diligence than has previously been considered necessary. uIAMs have the potential to act as valuable discussion-support or decision-support tools, enabling the likely costs and benefits of different strategies to be assessed (as e.g. see [43••,55]), and allowing for land-use planning to be optimised in much smarter ways than has been possible to date.

A multi-modelling uIAM approach provides tools, but it does not deliver solutions. The social challenges need addressing — about how services are weighted in the optimisation, who benefits, who loses, power relationships, land tenure; collectively the governance challenge. This challenge is one of great magnitude [56,57], and increasing competition for land services means it will become only more pressing. And, just as with climate change, knowing what we should so, and doing it, are completely different propositions. We do not underestimate the challenges either of such a complex modelling campaign, or the lessons we might learn from it, nor the implementation of those lessons, but we need a more strategic approach to using the land we have in a resource-constrained world.

Finally, returning to the third question we posed above, what if demand exceeds the ability to supply sustainably? Would this mean we might have to constrain demand, particularly for energy and food? Considerable systemic inefficiencies exist within the food system. The conversion ratios of calories and proteins into *healthy diets* is very poor at a global level (between 28 and 58% efficient): a third of global crop yields is fed to livestock [58]; a significant proportion of food is consumed in excess of caloric requirements, leading to an increasing global epidemic of obesity [59]; and a third of total food produced is lost or wasted in its conversion 'from farm to fork' [60••,61]. Dietary change and waste reduction offer considerable scope to address these systemic inefficiencies and so reduce pressure on land [6••,62••,63], allowing alternative uses and more sustainable land management.

Conflicts of interest

The authors have no conflicts of interest to declare.

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