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A nexus perspective on competing land demands: Wider lessons from a UK policy case study

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ABSTRACT

As nations develop policies for low-carbon transitions, conflicts with existing policies and planning tools are leading to competing demands for land and other resources. This raises fundamental questions over how multiple demands can best be managed. Taking the UK as an empirical example, this paper critiques current policies and practices to explore the interdependencies at the water-energy-food nexus. It considers how current land uses and related policies affect the UK's resilience to climate change, setting out an agenda for research and practice relevant to stakeholders in land-use management, policy and modelling. Despite recent progress in recognising such nexus challenges, most UK land-related policies and associated science continue to be compartmentalised by both scale and sector and seldom acknowledge nexus interconnections. On a temporal level, the absence of an over-arching strategy leaves inter-generational trade-offs poorly considered. Given the system lock-in and the lengthy policy-making process, it is essential to develop alternative ways of providing dynamic, flexible, practical and scientifically robust decision support for policy-makers. A range of ecosystem services need to be valued and integrated into a resilient land-use strategy, including the introduction of non-monetary, physical-unit constraints on the use of particular services.

1. Introduction

Water, energy and food are inextricably linked, and a failure to recognise the repercussions of actions and planning decisions in one area has often led to substantial consequences for another. For example, the current drive towards bioenergy as part of climate change mitigation strategies has significant implications for the availability of land and water with subsequent ramifications for food prices and global trade (Pimentel et al., 2008; Popp et al., 2014). Nexus thinking in this context represents a sustained effort to recognise the interconnections between these resources; to understand their interdependencies, synergies and trade-offs and to draw attention to competing demands and disparate visions (Stockholm Environment Institute (SEI), 2011). While nexus thinking is not new, it has lately emerged as a means of approaching societal challenges in an integrated fashion and has been used in fields as diverse as sustainable development (Bhattacharyya, 2006; Dasgupta et al., 2005), business (Davidsson, 2015; Sarason et al., 2006) and migration studies (Basarabă and Nistor, 2015; Sparke, 2006). The water-energy-food nexus was introduced at Bonn 2011, a precursor to Rio 2012, the UN Conference on Sustainable Development, although relevant discussions started at the World Economic Forum Annual Meeting in 2008 (World Economic Forum, 2011). The principle aim of nexus thinking is to transcend traditional policy and decision-making silos and develop approaches that build synergies across these sectors. Such a move calls for interdisciplinary and participatory—i.e. involving stakeholders—research and assessment (Stirling, 2015).

This paper takes the UK as a case study, focusing on land-use management as a key arena for nexus contests. Land is a precious and finite resource; of the 13 billion hectares available globally, most of the area suited for crop production worldwide is currently in use (Ajanovic, 2011). Future decisions regarding land use will therefore require decision-makers to balance a wide range of priorities on a complex evidence base. Over the last decade, the UK

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has seen development of numerous policies and planning trajectories with competing implications for land management (Foresight Land Use Futures Project, 2010). Examples of growing demands on both water and land are the expansion of housing and industry to sustain a growing population (Office for National Statistics, 2014); the increased production of biomass for a low-carbon energy system (Department for Environment Food and Rural Affairs (Defra), 2007; Department of Energy and Climate Change (DECC), 2012b; Forestry Commission, 2013) and for bio-derived plastics (Colwill et al., 2011); and the intensification of farming to support food security and increase self-sufficiency (Department for Environment Food and Rural Affairs (Defra), 2012; House of Commons, 2009).

Climate science forecasts significant impacts on global crop production (Knox et al., 2012) with consequences for food security (Vermeulen et al., 2012), livelihoods and the rural economy (Met Office, 2012; Wheeler and von Braun, 2013). Within the UK, climate change is likely to increase the frequency of droughts in the south and southeast (Met Office, 2011; Watts et al., 2015). While the UK is less vulnerable to climate change than other nations in lower latitudes (Met Office, 2011), the country's food security could still be at risk to climate impacts on domestic production, and through

Table 1
Examples of global, European and the UK policies affecting components of the water–energy–food nexus.

Sector	Global	European	UK
Agriculture & Fisheries	The Uruguay GATT Round, and establishment of World Trade Organisation	Common Agriculture Policy including Rural Development Regulations (RDR) Common Fisheries Policy Protected Food Names Protected Wine Names Animal By-Products Regulation	UK Bovine Tuberculosis Eradication Programme Farming Regulation Task Force Report
Energy	Kyoto protocol UN Framework Convention on Climate Change Copenhagen Accord	Renewable Energy Directive IEA/EU Oil Stock Holding Regulation Energy Statistics Regulation Energy Efficiency Directive Fuel Quality Directive TEN-E: Regulation (EU) No 347/2013 on trans-European energy networks	1965 Nuclear Installations Act 1989 Electricity Act 1993 Radioactive Substances Act 1995 Gas Act 2003 Energy White Paper 2007 Energy White Paper 2008Climate Change Act 2008 Planning Act 2011 National Policy Statements for Energy Infrastructure 2012 DECC Energy Security Strategy 2013 Bioenergy Strategy 2013Carbon Plan 2013 Energy Act
Water	1971 Ramsar Convention	Water Framework Directive	1975 Salmon and Freshwater Fisheries 1991 Water Industry Act 1991 Water Resources Act 2010 Flood and Water Management Act 2011 Water for Life – White Paper 2014 Water Act
Industry		2009 Eco-Design Directive	Statistics of Trade Act
Residential			2014 Green Deal 2014 Smart Meters
Conservation	1992 UN Conference on Environment and Development (Rio) 2012 UN Conference on Sustainable Development (Rio + 20)	Common Agriculture Policy including Rural Development Regulations (RDR) 1982Convention on the Conservation of European Wildlife and Natural Habitats (Bern) 1992Habitats Directive, 2009 Birds Directive	1981 Wildlife and Countryside Act 2006 Natural Environment and Rural Communities Act 2009Control of Trade in Endangered Species (Amendment) 2010Conservation of Habitats and Species Regulations 2011 Natural Environment White Paper 2012 National Planning Policy Framework
Forestry			2013 Forestry & Woodlands Policy 2013Chalara Management Plan
Recreation			1857 Inclosure Act 1876Commons Act 2000Countryside and Rights of Way Act 2009 Marine and Coastal Access Act
Other			2008 National Infrastructure Planning Act

its heavy reliance on food imports and global supply chains. The country's population is projected to grow from the current 63 million up to 77 million by 2050 (Office for National Statistics, 2014), with corresponding increases in demand for food, energy and water. The UK has a land area of 24.4×10^6 ha (Hart et al., 2013; LUCAS, 2014). If this land area was distributed equally across the UK population, each person would have 0.38 ha, which is comparable to Germany and half that of France. Globally, with the land being a fixed resource and with a growing population, pressures on land use will inevitably intensify.

Although there is much uncertainty about longer term projections of population, climate change and other socio-economic indicators (Intergovernmental Panel on Climate Change (IPCC), 2013; Nath, 2013), they are symptomatic of broad trends that affect the nexus. With these challenges in mind, this article explores the interdependencies at the water–energy–food nexus and critiques existing policies and approaches affecting land availability. It sets out a new agenda on resilient land use to support the development of more integrated policy- and decision-making. The lens of land use is taken to consider the policy environment from a UK-centric perspective.

Discussion in this paper is limited to fresh water resources available for human consumption and to the agricultural production of food rather than the full supply chain, except to consider how globalisation might affect land requirements for food and bioenergy. The geographical focus is the UK including implications at regional and local levels, within the context of key European and global trends both affected by and affecting UK land use. All types of the UK's land are considered here, not just agricultural uses. Since a complete assessment of all interactions of the nexus is beyond the scope of this paper, this synthesis is limited to considering nexus implications for land use and to raising questions about the resilience of the existing system.

The paper first questions the concept of 'resilience' at the nexus, before analysing some of the main policies currently influencing UK land use. It then questions how current land uses and related policies affect the UK's resilience in the medium to long term (i.e. at least 10 years into the future) to the challenges of climatic changes, delivering deep cuts in greenhouse gases and changing demand for resources. Different temporal and spatial scales are considered, including potential impacts of the UK's current decisions on other countries and future generations. The concluding section poses important questions regarding future land-use management, policy and modelling aimed at one or more components of the nexus.

2. Challenges in defining resilience of land uses to socio-environmental challenges

Resilience is a pervasive term, yet its meaning is ambiguous and definition contested (Brand and Jax, 2007; Standish et al., 2014; Walker et al., 2006). In 1973, Holling (1973) defined resilience as a "measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables", referring to an ecosystem's ability to tolerate disturbance without significant change to its ecological stocks, processes or functions (Walker et al., 2006, 2004). Recent studies recognise the entanglement of social and environmental systems (Anderies et al., 2006; Béné et al., 2015; Folke, 2006; Folke et al., 2002; Walker et al., 2006), viewing resilience as a system's capacity to adapt or even transform in response to socio-environmental changes such as climate change, population growth and consumption.

Resilience at the water–energy–food nexus is complicated. Society often expects contrasting outputs from each sector, with each encompassing different stocks and flows, and exposed to a multitude of socio-environmental changes. For example, in the water sector, resilience may be framed in terms of the sector's capacity to balance demands for water from production of food and energy with those of ecosystems, to ensure abstraction remains sustainable. Simultaneously, following the later definitions, resilience refers to the sectors' accommodation of a rising population and climate change impacts that will affect both catchment hydrology and patterns of demand (Watts et al., 2015). By contrast, resilience for the energy sector is not only about available and affordable supply (Chaudry et al., 2009), but also about the sector's capacity to contribute to climate change mitigation and adaptation. The drive to decarbonise and adapt energy networks in the UK is a significant policy imperative that contributes to the long-term resilience to climate change of not only the energy industry, but also much of society.

Resilience at the nexus must also consider the interdependence of these sectors and their interaction with human and natural well-being, as the examples above suggest. A healthy water sector is important for the resilience of energy and food sectors. Similarly, achieving resilience for the energy system is problematic for the water sector, as energy generation requires water resources. This is evident in the debates on shale gas, with its exploration and extraction having consequences for water availability and quality (Stamford and Azapagic, 2014). Tidal energy might lead to the eutrophication of estuarine ecosystems, a water management

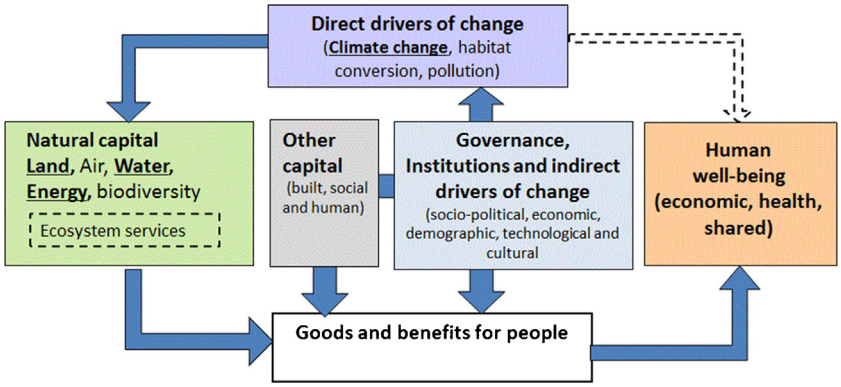

Fig. 1. The 'ecosystem service framework' from by the UK National Ecosystem Assessment showing possible interactions between governance and institutions and the management elements of the nexus (modified from UK National Ecosystem Assessment (UKNEA), 2014, to include emphasis on land, water and climate change and the inclusion of energy as a form of natural capital).

issue that several decades of international policy have sought to address (Kadiri et al., 2014). Furthermore, the production of bioenergy has implications not only for water management, but also for the availability of land for food production (Knox et al., 2013; Pimentel et al., 2008; Popp et al., 2014). These examples illustrate the interdependent nature of resilience at the nexus, raising the fundamental questions of whether and how policy might better enable systemic resilience to resource constraints and a changing climate. Any new approaches must go beyond the usual monitoring and modelling to examine the interactions between the nexus components.

3. Policy impacts on land use

Land use is influenced by, among other factors, population size, expansion or contraction of particular economic sectors, agricultural practices and climate change. Most of these factors are influenced by policy. Table 1 gives examples of global, European and the UK policies affecting components of the water–energy–food nexus in different sectors of the economy. In addition to legislation, there are various initiatives established at different levels of governance. For example, the Scottish Government has funded the development of the Farming for a Better Climate website (Scotland's Rural College (SRUC), 2013), which offers practical measures farmers can use to reduce greenhouse gases, while the Welsh Government (2013a) established the Land Use Climate Change Group to consider how agriculture and rural land use could reduce climate change and help people to adapt.

Land supplies many services and products, from food and materials to clean water and biodiversity to space for power plants and pipelines. These are captured within the concept of 'ecosystem services' developed and advanced, among others, by Daily (1997), Costanza et al. (1997), de Groot et al. (2002) and a range of Millennium Ecosystem Assessment reports (Millennium Ecosystem Assessment, 2005). The UK National Ecosystem Assessment (UK National Ecosystem Assessment (UKNEA), 2014) defines ecosystem services as "the benefits provided by ecosystems that contribute to making human life both possible and worth living". The processes of valuing and allocating land are directly related to the management of ecosystem services, which is yet to be appreciated by the nexus discourse (Rasul, 2014). The 'ecosystem service framework' (Fig. 1) highlights possible interactions between governance and institutions and the management of elements of the nexus. Land and water are key components of this conceptual framework that also includes the role of governance and other forms of capital. Although there is a strong emphasis on the impacts of climate change, the framework does not explicitly mention energy. A scientific approach compensating for that, to some extent, is EnergyScapes that links the components of the nexus through the ecosystem services they influence, by examining the interactions between land-based renewables, habitats and ecosystem services (Howard et al., 2013).

3.1. Energy sector

A more coherent and joined-up policy realm requires that the 'ecosystem services framework' include energy alongside other ecosystem services. The Natural Capital Committee (2014), an independent advisory body to the UK government, defines ecosystem services, or natural capital, as "the elements of nature that directly or indirectly produce value to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions". They indicate that it includes sub-soil assets such as fossil fuels, as well as the processes that give rise to wind and precipitation. Like other forms of natural capital, these energy sources are used to derive benefits, for example, heating and transportation. A range of energy sources also feed into the production of electricity that powers lighting, communications and conversion of materials through processes and manufacture. Hence it is appropriate to include energy within the Natural Capital box in Fig. 1, distinguishing between renewable and non-renewable energy.

Such exclusion of elements of the nexus is evident in some of the current analyses and policies. In this vein, the UK 2012 Bioenergy Strategy poorly accounts for the implications of bioenergy targets for food, water and land use both within and outside the UK. A recent life cycle assessment, completed by the UK Government's Department for Energy and Climate Change explores greenhouse gas emissions for the UK importing biomass from North America (Stephenson and MacKay, 2014), in isolation from other impacts. While more established UK energy sources such as nuclear power are typically assessed on wider impacts (Azapagic et al., 2011), the emphasis is on pollution and public perceptions rather than on nexus impacts. The nexus focus is however becoming essential, as rapidly increasing demand for resources is compounded by climate change pressures. One example of attempting a nexus perspective is a major UK energy company's claim to minimise negative impacts of bioenergy production on food supply, soil and water quality (Drax, 2012).

At the EU level, impact assessments of energy policies are common. For the EU's Renewable Energy Directive (European Parliament, 2009), Fonseca et al. (2010) provide a comprehensive overview of the medium-term impacts of biofuels on agricultural markets and on land use both inside and outside the EU. Following the EU's example, other governments may want to consider such studies in future and to cover a wider range of impacts on water, food and land. However the question remains whether the policies and strategies under consideration will be modified if assessment studies raise concerns about the impacts.

Some overarching energy policies pay even less attention to the nexus complexity than sector-specific legislation does, perhaps due to their general nature being at the expense of depth. The UK Energy Act (2013) does not refer to either food or land use, while it only mentions water in a narrow legal context. By contrast, the latest Carbon Plan, setting out how the UK will decarbonise its energy system, provides a lengthy analytical annex on "sustainability and wider environmental impacts" (Department of Energy and Climate Change (DECC), 2011). It highlights the UK Government's commitment "to champion a more integrated approach to global food security by governments and international institutions that makes the links with climate change, poverty, biodiversity, energy, water and other policies" (Department of Energy and Climate Change (DECC), 2011). The Carbon Plan refers to the importance of valuing ecosystem services and of the UK National Ecosystem Assessment (see Fig. 1). This approach is an important step towards a more integrated framework for energy policy.

3.2. Agriculture and forestry

The main land uses in the UK are agriculture and forestry, accounting for approximately 77% (18.7 Mha) and 8.5% (2.1 Mha) of the total land area, respectively (Angus et al., 2009; Hart et al., 2013). Policies aimed at agriculture (assumed as a proxy for the food element of the nexus) and forestry often overlook many aspects of the nexus. In fact it is rare for agriculture and forestry to be considered in the same document. The EU Common Agricultural Policy (CAP) is concerned with maintaining land in good agricultural and environmental condition, whereas EU forestry policy has tended to develop separately. With "increasing links between international food, feed, fibre and fuel markets" (European Commission, 2013), the EU has recognised that its new forestry policy framework needs to "allow synergies with

other sectors" (ibid.). This is particularly relevant given that bioenergy and other bio-derived materials (e.g. for construction, chemical production and pharmaceuticals) can be sourced from both forestry and agriculture (potentially competing with food production), while water quality and flood prevention often require a landscape approach that combines trees, soils and agriculture. Food production competes with the energy sector not only for materials and land but also for fresh water, for example in the case of such food-related water uses as agricultural irrigation and fish farming (Ajiero and Campbell, 2014). In this context, the development of a land-use strategy by the Scottish Government (2011) does bring together food production, forestry, energy and water. Scientific research in integrative disciplines such as agroforestry (Graves et al., 2007; Palma et al., 2007), landscape planning (Jackson et al., 2013) and life cycle assessment (Chatterton et al., 2015) can also offer tools and bio-economic models to inform some of the synergies and trade-offs. In addition, the LUCAS Land Use/Cover Area Survey (LUCAS, 2014), which allows the assessment of multi-functional land use, can be a useful resource.

While the UK's 2013 Forestry & Woodlands Policy Statement (Department for Environment Food and Rural Affairs (Defra), 2013) mentions that woodlands play a role in providing clean water and energy (fuel wood), no analysis is provided of how either water or energy would be affected by implementing the policy. Similarly narrow legislation is the EU's CAP that tends to marginalise ecosystem services, other than agricultural products. Some studies suggest that a 'greening' of the CAP would improve its impacts on ecosystem services and make it "an exemplar for redirecting agricultural policies [. . .] toward sustainability" (Plieninger et al., 2012). However the progress on 'greening' is limited; for example, the requirement for 5% of some arable land to be designated as 'ecological focus areas' has been undermined by including nitrogen-fixing crops within the designation. Some experts (Bateman et al., 2013; Brady et al., 2012; Maes et al., 2013) argue that the complexity of the CAP precludes straightforward answers and that its impacts vary widely at different scales. This paper concurs that the interdependencies between the nexus components need to be assessed at global, regional and local scales, if long-term coherence of policies at the nexus is to be achieved.

In relation to a different aspect of food, current agricultural policies contain no strategy to be integrated with nutrition guidelines and, in turn, nutrition guidelines do not account for the impacts of recommended diets on the nexus (van Dooren et al., 2014). Food is a necessity, but diets are typically shaped by choice, which in wealthier countries is extensive. A combined assessment of environmental and health impacts of food policies would contribute to the debate about needs vs. wants. Such an approach to policy-making would highlight issues of equity and distribution both within and between generations.

3.3. Water sector

UK water-related policies have generally acknowledged that the water sector is inextricably linked with energy generation and food production, among other sectors of the economy (Defra, 2011). Agriculture is evidently better integrated with the management of national water issues than the energy sector is. For instance, the Rural Development Programme for England (Department for Environment Food and Rural Affairs (Defra), 2014b) organises 'Efficient Water Management' events, and the Farming and Forestry Improvement Scheme (Department for Environment Food and Rural Affairs (Defra), 2014a) provides funding for and audits of resource efficiency, including water. Despite these efforts, as yet no policies provide genuinely integrated management of water, energy, food and land. The UK Water Act 2014 makes no mention of either energy/electricity or land use. While 'Water for Life', a White Paper on water resource management, recognises that the energy industry is a significant consumer of water (Defra, 2011), it provides no figures to illustrate the scale of interaction. Since its publication, such estimates have been produced and/or updated, in relation to established and new technologies. The Environment Agency (2013) confirms that the electricity sector is currently the largest water abstractor, accounting for more than 50% of licensed abstraction, with 95% used by hydroelectricity power plants and the rest by thermal power plants. However water used in this sector is non-consumptive i.e. water is returned into the catchment after use, usually with similar quantity and quality as before use. By contrast, in agriculture, water abstractions for supplemental irrigation are almost entirely consumptive (Weatherhead et al., 2015).

Among forthcoming technologies, carbon capture and storage could nearly double the use of water by power stations (Department of Energy and Climate Change (DECC), 2011). While many renewable energy options require water, demand-side mitigation can save it by reducing demand for energy and, hence, for cooling in thermal power stations (Wallis et al., 2014). In addition, displacing thermal power stations with wind and solar energy sources would reduce absolute water demand (Carter, 2010; McDonald et al., 2012).

4. Issues arising from policies and visions competing for the use of land and water

4.1. Establishing policy scope

Despite the obvious interdependencies within the nexus, there is a legacy of compartmentalising issues within isolated government departments and agencies (Miles and Trott, 2011; National Audit Office, 2013). In terms of scope, both policies and modelling studies often fail to consider interconnections, synergies and trade-offs between the components of the nexus. Some policies do not acknowledge potential conflicts and trade-offs even between objectives within a single document, let alone considering implications of policies in other areas. A prime example is in the four goals within the 2003 and 2007 Energy White Papers (HM Government, 2003, 2007)—emission reductions, energy security, economic growth and reduction in fuel poverty—where the complexity of the issues is not addressed. Where such interdependencies are recognised (as evident in the recent CAP reform), the approach is piecemeal and contradictory.

Globally, policies on water and energy are still further disjointed, including in terms of their governance (Rodriguez et al., 2013) and, as the analysis here shows, the same holds for the management of the rest of the nexus. A similar disconnect exists not only *between* but also *within* sectors. For instance, within the urban water sector such services as clean water supply, wastewater treatment and floodwater drainage are typically delivered by separate entities and not coordinated, as well as being isolated from other urban planning processes (Bahr, 2012). There is also a complex issue of agricultural policies being separate from groundwater management where even existing 'best practices' have thus far failed to achieve a sustainable use of groundwater (Shah, 2014).

Current UK policies give an impression that the components of the nexus exist in isolation, for example, that the boundaries between land and water are distinct. However such boundaries do not exist in reality since land underlies water (lakes and rivers), water underlies land (aquifers and water tables) and there are intermediate habitats (wetlands, intertidal stretches and temporary water bodies) where both overlap. The way land is managed not only determines water flows, energy use, productivity,

environmental regulation and cultural benefits, but also affects other ecosystem services at a range of spatial and temporal scales.

4.2. Examining spatial scales

Bateman et al. (2013) argue that spatially disaggregated modelling demonstrates wide variations between results for different UK regions in terms of how the monetary valuation of ecosystem services enhances the value of land. This result suggests that nationwide land-use policies may be less effective than those tailored to particular regions. Locally targeted planning might yield even more powerful insights for conventional land-use models, although it would undoubtedly increase the complexity of how national decision-making feeds into local planning. In addition, the local scale offers an opportunity to explore how the nexus problems can be addressed on the demand side, e.g., by changing people's behaviour and practices to reduce consumption.

Furthermore, the impacts of particular UK policies on UK land are rarely mentioned in impact assessments of policies in non-agricultural sectors (Department for Environment Food and Rural Affairs (Defra), 2014c; Department of Energy and Climate Change (DECC), 2012a, 2013). Some government documents are, however, starting to acknowledge that the UK's policies are not only affecting land use nationally but also could have major global impacts. For example, the Carbon Plan (Department of Energy and Climate Change (DECC), 2011) warns that, in one of its scenarios, the UK's demand for bioenergy would affect about 4.5 million ha both in the UK and abroad leading to the loss of habitat and other ecosystem services. In addition to the potential land-use impacts, there is a concern that the UK 2012 Bioenergy Strategy might lock the country into an avoidable dependence on biomass imports (Welfle et al., 2014). Yet, the UK 2012 Bioenergy Strategy itself takes little account of such consequences (Department of Energy and Climate Change (DECC), 2012b).

Negative impacts of the UK policies on other countries (including such issues of 'land grabbing' and 'water grabbing') raise concerns about global equity. *Intra*-generational trade-offs in terms of the distribution of land and resources between industrialised and industrialising countries, as well as between poorer and better-off groups within nations, are rarely acknowledged. A vital international agenda with many nexus interactions is the Sustainable Development Goals adopted in September 2015 (United Nations, 2015). Although the SDGs have a strong focus on justice and equity, the nexus approach could be useful for further highlighting inter-generational trade-offs, as the Goals do not extend beyond 2030. Similarly, trade-offs between different ecosystem services deserve more attention than the SDGs currently give them, and the nexus lens is essential for making such trade-offs implicit. These issues of fairness will be aggravated as climate change intensifies, ultimately affecting *inter*-generational equity in irreversible ways.

4.3. Reconciling temporal scales

At a temporal level, the absence of an overarching UK land-use vision implies that longer-term interactions and interdependencies within the nexus are not considered. Accordingly, trade-offs between generations are typically neglected when designing and implementing policies affecting land use. For example, there is little in-depth investigation of how water, energy and food/agricultural policies are going to play out for the subsequent generations. Cost-benefit analysis is increasingly used for ex-ante policy impact assessment (Livermore and Revesz, 2013). While the method has improved technically over the years, it is still controversial (Ackerman and Heinzerling, 2004), and even deemed unsuitable for the planning that affects land use and ecosystem services (Beukers et al., 2012; Wegner and Pascual, 2011).

It is important to emphasise that elements of the nexus will have very different time horizons. This is illustrated by the dissimilarity in both short-term projections and strategic (i.e. longer-term) planning horizons in the water and energy industries. The timescale of water-related short-term demand forecasts is weeks to months, with the energy industry relying on forecasting minutes to hours ahead (Rodriguez et al., 2013). For the longer term, the UK's water industry produces 25-year forecasts every 5 years (Environment Agency, 2014), whereas the National Grid's future energy scenarios look further ahead out to 2030 and 2050 (National Grid, 2014). The Committee on Climate Change has established 5-year time steps and CO_2 budgets for the implementation of the Kyoto Protocol and succeeding emission reduction targets, but these were drawn up without any consideration of the 5-year Environmental Agency forecasts (Committee on Climate Change (CCC), 2008).

While both operational and strategic timelines are important for infrastructure investment, this paper emphasises the medium- to long-term horizons defined here as 10 years and longer. At the same time, a short-term horizon (i.e. under 10 years) is essential for avoiding policy lock-in. Large infrastructures tend to last for decades and to co-evolve, "intimately inter-linked" (Unruh, 2000), with institutions; therefore current investment decisions are path-dependent. If such decisions cater to either short-term interests or insular long-term objectives without considering implications for other elements of the nexus, there is a danger of locking out better (lower-carbon, more water-efficient, less polluting) technologies, practices and institutions. For example, while the production of shale gas in the UK may be beneficial for the country's medium-term energy security, investment in this fossil fuel is incompatible with the Government's decarbonisation agenda (Broderick et al., 2011).

The importance of both long-term priorities and short-term action is evident when it comes to climate change issues. Temperature increases are approximately linearly correlated with cumulative carbon emissions (Intergovernmental Panel on Climate Change (IPCC), 2013), and higher carbon dioxide concentrations will continue to alter the climate for many decades. For these reasons, strong mitigation action in the short term is essential if the world is to minimise severe long-term climatic changes. The current pledges of major emitting countries and regions fall short of the emission reductions that need to take place by 2020 to stay below a dangerous climate change threshold later in this century (United Nations Environment Programme (UNEP), 2014; United Nations Framework Convention on Climate Change (UNFCCC), 2015). If meaningful measures aimed at cutting emissions continue to be postponed, the infrastructural, institutional and policy lock-in will preclude decarbonising swiftly enough to avoid dangerous climate change. This would severely challenge the UK's and global resilience affecting all nexus components.

5. Discussion: Implications for land-use policy

This paper has considered policies aimed at the sectors of water, energy and food production, covering the policy scope, spatial and temporal aspects of the nexus in relation to competing land uses. Based on the analysis here, key challenges for the nexus include understanding the geographical scales and the duration of impacts of different activities; *inter*-generational trade-offs (i.e. between the present and future generations) in line with sustainable development goals; *intra*-generational trade-offs (e.g. between industrialised and industrialising countries, as well as between poorer and better-off groups within countries); and the scientific robustness, certainty and confidence in linking the

nexus components. A short-term challenge of the nexus approach is the hidden, or 'transaction', costs of interdisciplinary and participatory research (van Rijnsoever and Hessels, 2011) and of working across sectors in general. For example, such activities as searching information about new domains, bringing disciplines and stakeholders together, negotiating differences, and taking decisions are likely to be more time-consuming and expensive in the short term than avoiding the nexus approach altogether. Recognising the trade-offs is a significant challenge that will necessitate joined-up thinking and collaboration. Failure to do so risks undermining countries' standards of living and resilience to climatic change and to global population growth in the longer term.

5.1. Present and short-term policy implications

Existing tools and metrics do not provide appropriate guidance for the availability of land in light of the nexus challenges. This can in part be explained by the quality and availability of data, the accuracy of projections, and limitations of policy advice from models and other decision-making tools. Another major reason is insufficient coordination between and within modelling teams, government departments and the industry. While models, tools and policies in each of the nexus-related sectors have achieved high sophistication, they fall short of an integrated perspective on land use. Such integration would add further complexity and introduce new methodological and data challenges.

Two approaches are being developed to tackle this challenge. Firstly, pairwise integration of the nexus components is gaining momentum, with some modelling teams starting to address, for instance, the energy-water interactions (Bhatt et al., 2013; Lawrence Berkeley National Lab, 2010). This approach is not without difficulties. In particular, water models are much more spatially 'aware' of underlying geography but usually have a much coarser timescale than energy models (Rodriguez et al., 2013). Another example of a pairwise combination is the Integrated Land and Water Resources Management (ILWRM) that derives from the Integrated Water Resources Management. The latter was developed in the early 1990s (Hufschmidt and Tejwani, 1993) and started including land about a decade later (Calder, 1999, 2005). The nexus approach, by definition, would call for expanded ILWRM, given deep interdependencies between the different nexus components.

Secondly, a focal lens of land can help integrate all components of the nexus to address systemic resilience. Burgess et al. (2012) develop a framework to map demand for energy, food and wood, following a balance sheet approach (note that they do not consider water). This framework explores trade-offs between different ecosystem services and can be applied at a variety of scales, from national to local.

Similar to modelling teams, the private sector has thus far been highly fragmented and shaped predominantly by disjointed policies (e.g. CAP in the agricultural sector and abstraction licensing strategies in the water sector). Industries retain much of the control over their own area, be it energy, food, water or land. Their focus is typically short-term, and coordinated management of the nexus elements is all but non-existent. For example, potential conflicts between the water and power sectors are prompted at least in part by policy and responses to it. Water companies measure leakage at night when water use is low and, hence, there is virtually no water flowing through the pipes and it is quiet enough to detect leakage in urban areas (ABB Limited, 2011); however smart meters are supposed to switch on certain appliances, such as washing machines, at night to reduce peak demand for electricity during the day. If smart meters were rolled out on a large scale, as envisaged in many energy policies (Department of Energy and Climate Change (DECC) and Ofgem, 2013), current approaches to identifying leakage would become inadequate.

On the other hand, many in the private sector and in the Government are starting to appreciate the importance of coordination and integration at the nexus. To this end, an industry group with an interest in agriculture has recently produced an integrated vision for the UK's land use: "By 2030, UK agricultural land will be optimised to support the multiple needs of a 70 million population and deliver an improved and sustainable natural environment." (Montague-Fuller, 2014). While this land-use vision acknowledges manifold demands on land, it is essential to recognise that a single optimal solution at the nexus is impossible due to systemic complexity within a constantly changing environment. To genuinely embrace nexus thinking, decision-making needs to balance short-term optimisation with resilience, iterative adjustment and learning-by-doing.

Despite the absence of a national strategy for resilient land use, some progress has been achieved by both the UK Government and devolved administrations. In 2010 the Government Office for Science published Foresight Land Use Futures (Foresight Land Use Futures Project, 2010) followed by a range of reports, including Making Space for Nature (Department for Environment Food and Rural Affairs (Defra), 2010), The UK National Ecosystem Assessment Follow-on (UK National Ecosystem Assessment (UKNEA), 2014), and The State of Natural Capital (UK Natural Capital Committee, 2014). The Welsh Government (2013b) produced The White Paper on the sustainable management of Wales' natural resources in 2013 leading to a consultation on an Environment Bill. What these documents have in common is an attempt to attribute (monetary or otherwise) value to ecosystem services. Yet this progress in the Government's thinking regarding the multifunctional use of land is not sufficient to address the ongoing environmental and demographic changes, as the rate of these changes is currently much faster than the pace of policy-making. Accordingly, the inadequacy of current policies and ensuing industry practices is likely to have negative repercussions in the longer term.

5.2. Medium- to long-term policy implications

One of the key questions for land-use planning is how the physical and socio-economic implications of a significantly changed climate may play out for the water-energy-food nexus and their relationships with land. Alongside the changing climate, inadequate policies are likely to become another major threat to the UK's ecosystem services in the longer term i.e. at least 10 years into the future. Existing initiatives tend to make optimistic macroeconomic assumptions about the release of land from agriculture as they presume a steady increase in mean arable yields. However in practice such arable yield increases are not being achieved in Western Europe (Knight et al., 2012). Based on scenarios of how current policies might play out, Montague-Fuller (2014) estimates that, by 2030, additional demand for land would exceed supply by up to 7 million ha, which is more than a third of the UK's agricultural land.

In addition to the 'yield gap' and shortage of land, other medium- to long-term vulnerabilities are analysed by the Foresight Land Use Futures Project (2010). It identifies nine areas that are expected to exert extra pressure on the land-use system in the longer term, including agriculture, forestry, conservation, water resource management, energy, flooding, housing, transport and recreation. The study shows that developments in each of the areas are accompanied by trade-offs, with highly uncertain future consequences (Foresight Land Use Futures Project, 2010). The report predicts increasing population density and smaller houses,

which is contrary to many people's aspirations and might cause social tensions. At the same time, this trend would arguably facilitate energy savings and lower emissions from buildings. However when transport and commuting are taken into account, the evidence on energy savings becomes contradictory. With resource constraints on water, food and land, and with impacts partly determined by location, the emerging picture is highly complex and dynamic.

The dynamism and, hence, potential instability of the nexus interactions is likely to increase, given ongoing climatic changes and, possibly, rapid mitigation and/or rapid adaptation measures (particularly response-mode adaptation, which tends to be fast-paced, when dealing with a crisis). While coupled socio-economic and natural systems are by definition dynamic, current policies risk further destabilising them in the longer term and jeopardising the UK's resilience to the challenges of climate change and resource constraints. It is worth noting that the aim of improving the resilience of the food, water and energy sectors requires a constant process of delicate balancing of different parts of the system. This ongoing challenge calls for an integrated, long-term perspective on land use and ecosystem services.

As discussed throughout this paper, a major systemic challenge of an integrated land-use vision is that government departments struggle to manage a nexus, as they focus on the components not the interactions. Considering the system lock-in and the lengthy policy-making process, it is essential to develop alternative ways of providing dynamic, flexible, practical decision support for policy-makers both for the near term and further into the future. These decision support tools should be made available to the wider public to promote evidence-based debate. This paper suggests the need for new protocols to transparently link policy to its potential impacts across space and time; such protocols should have both scientific and statistical rigour. First and foremost, a wide range of ecosystem services need to be valued and integrated into a resilient land-use strategy; pivotal here is the inclusion, on an equal footing, of non-monetary, physical-unit constraints on the use of particular services. Ecosystem services and their societal benefits are often implicit within the existing tools and metrics. For instance, it is advisable to include energy in the ecosystem service discourse (see Fig. 1), as it increasingly drives land change in terms of bioenergy. Water is also frequently excluded from assessments (Bateman et al., 2013; Burgess et al., 2012). Yet Bateman et al. (2013) find that an inclusive assessment of several ecosystem services, in addition to agricultural products, increases the value of land. There is therefore a need for a suite of valuation systems that span the three components of the nexus and provide policymakers with a well-balanced framing of the issues – rather than a simple monetary evaluation.

Such valuation could be built along the lines of multi-criteria analysis, although it must be recognised that individuals and groups will have their own way of valuing that may not be stable. Stakeholder engagement could help capture these diverse valuations and negotiate more inclusive policies. Involving stakeholders using participatory methods would also give vital cross-sectoral insights that current models may lack, for example, grounded assumptions about the amount of land available, as well as local and regional knowledge to complement macro-economic considerations. Stakeholder engagement, combining quantitative assessments, qualitative information and problem-solving techniques can gather different interests around the same table to work together.

6. Conclusions

This paper has identified how viewing policy from the perspective of the water-energy-food nexus might improve the delivery of a resilient and sustainable land-use system. The UK has been used as a case study to demonstrate how the interdependencies between water, energy and food are overlooked in current policies, highlighting some of the consequences. A tradition of disjointed management often leaves energy, food and water in competition, with policies and tools ill-equipped to provide appropriate and sustainable solutions. There are many specialised metrics, models and decision-making tools designed to quantify the capacity of land required for particular outcomes. However such tools tend to have serious limitations, such as heavy reliance on macro-economic factors, disregarding interactions within the nexus and excluding qualitative information. A further challenge arises from stakeholders not engaging around nexus issues, but remaining firmly within their own sectors. The value of qualitative and stakeholder aspects for land-use policy-making tends to be underestimated.

Despite recent progress in recognising the challenges of the nexus, most UK land-use policies focus on either food or energy provision, remain compartmentalised by both scale and sector and seldom acknowledge other nexus components. The inadequacy of existing approaches is particularly stark when faced with both immediate and long-term challenges of climatic and demographic changes. Land-use models and tools often cover national or regional scales, with insufficient granularity to provide appropriate guidance for management at a local (catchment) level, failing to both reflect local capacity and contribute to specific local goals and visions. Similarly, but at the other end of the geographical spectrum, land models fail to adequately capture global scale issues, both in relation to competing demands for the same resource and in considering indirect impacts of domestic policies on the land and water quality and availability elsewhere.

In the medium to long term, the insularity and short-sightedness of land-use policy is likely to jeopardise the resilience of the UK to climate change impacts, as well as its ability to severely curtail its greenhouse gas emissions in line with the Paris Agreement, particularly when set against a backdrop of increasing and competing demands for water, energy and food. Moreover, decisions taken within the UK could degrade the resilience of other parts of the world to their own nexus-related challenges (such as the resilience of food supply chains).

This analysis of the land-use challenges in relation to water, energy and food raises specific research questions and, more importantly, provides the necessary context for developing a crucial nexus research agenda, for example: Where are the main vulnerabilities of the UK's land system, given current trends and policies? How can policymakers be encouraged to factor in the various interdependencies of the nexus and who would have the authority to oversee this? What underpins the design and implementation of an overarching longer-term vision for UK land use, taking into account both spatial and temporal interdependencies? What further research is needed to assess the resilience of different blends of nexus components?

A new scientific approach is required that moves away from the traditional Popperian experimental reductionism (Popper, 2003). Mathematical models and statistical analyses can generate new insights and hypotheses; however, methods of meaningfully testing hypotheses on complex systems, assessing confidence and validating outputs are still missing or not commonly applied.

Finally, what is also needed is a radical overhaul of the current system of policy- and decision-making, supported by stronger, integrated and more interdisciplinary research. Researchers have to broaden their single-discipline perspectives, engage more deeply with stakeholders and view ecosystems services as a whole, instead of focusing on only those that are straightforward to study or quantify. As a start, a new type of land-use model is needed that is capable of describing multi-functional land-use and

management choices in the context of nexus issues and a changing climate. The outputs of the model must be in forms that can be debated by policy-makers and the general public, and that can address the diversity, variability and negotiation strategies of different groups. A new modelling framework needs to coherently reconcile competing demands for land use and other resources, identify scope for partial synergies between such demands and assess impacts on the ability of other countries to meet their own needs. The building blocks for such an integrative research programme are already in place, but it is a major challenge to deliver an integrated solution; it will require buy-in and trust from both research funders and policy-makers. Ultimately, the integration of the nexus at different scales would help unlock the full value of land and ecosystem services – as well as see beyond such instrumentalist views to consider the wealth of cultural and non-human attributes of the natural world.

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