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Assessing climate change risks to the natural environment to facilitate cross-sectoral adaptation policy

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Summary

Climate change policy requires prioritisation of adaptation actions across many diverse issues. The policy agenda for the natural environment includes not only biodiversity, soils and water, but associated human benefits through agriculture, forestry, water resources, hazard alleviation, climate regulation, and amenity value. To address this broad agenda, the use of comparative risk assessment is investigated with reference to statutory requirements of the UK Climate Change Risk Assessment. Risk prioritisation was defined by current adaptation progress relative to risk magnitude and implementation lead times. Use of an ecosystem approach provided insights into risk interactions, but challenges remain in quantifying ecosystem services. For all risks, indirect effects and potential systemic risks were identified from land use change, responding to both climate and socioeconomic drivers., and causing increased competition for land and water resources. Adaptation strategies enhancing natural ecosystem resilience can buffer risks and sustain ecosystem services but require improved cross-sectoral co-ordination and recognition of dynamic change. To facilitate this, risk assessments need to be reflexive and explicitly assess decision outcomes contingent on their riskiness and adaptability, including required levels of human intervention, influence of uncertainty, and ethical dimensions. More national-scale information is also required on adaptation occurring in practice and its efficacy in moderating risks.

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1. Introduction

Climate is a major influence on the variability of natural processes. Abundant evidence is available to show past climate change was associated with considerable environmental change [1]. This sensitivity implies anthropogenic climate change will bring substantive shifts in the natural environment together with associated consequences for humans, notably for food and water, livelihoods, security, identity, and health and well-being. However, the natural environment is also characterised by complex systems behaviour, including feedbacks and thresholds, with a propensity for indirect and surprising outcomes [2]. An increasing human footprint means much of the natural environment has been modified, also affecting processes and outcomes [3]. This complexity means there are fundamental challenges in deciphering, predicting and communicating climate change as a basis for developing constructive policy responses. Scientific contributions have identified a wide range of actual and potential impacts for the natural environment and indicator-based approaches have used trend identification to highlight key issues for policy [4]. However, much less emphasis has been placed on the mediating role and effectiveness of adaptation processes in the causative chain leading to impacts. Consequently, policy implications, especially those associated with different strategies for intervention, have usually not been fully articulated. In addition, the diverse array of impacts has often caused consternation amongst policymakers seeking to know which are most important and therefore the policy relevance of current scientific assessments, such as IPCC reports, has been questioned [5]. Similarly, use of indicators for policy communication has been criticised for scientific inconsistencies including limited consideration of uncertainties and non-linearities [6].

In this contribution, a risk-based framework to bridge between science and policy for national-scale assessment is examined. The primary goal was to address a policy demand for a consistent and unified evidence base to facilitate joined-up adaptation actions for the natural environment and its multiple societal benefits. Utility of an ecosystem-based approach to facilitate integrated assessment of human-environment interactions is therefore also investigated. Specific reference is made to evidence appraisal for the UK Climate Change Risk Assessment (UKCCRA), a statutory procedure required by Act of Parliament on a 5-year cycle to inform national adaptation policy [7]. Examination is restricted to terrestrial, freshwater and coastal environments, with progress for marine environments reported elsewhere [8]. Findings are used to provide recommendations for a more cohesive science-policy interface as a basis for enhanced decision-making on climate change.

In principle, a risk-based structure provides considerable scope to unify knowledge and deliver coherent climate change policy responses. Policy-making objectives in general are often strongly associated with risk management, hence explicit characterisation of risks to policy outcomes can provide direct interface with the decision-making process [9]. Risk assessment as a structured procedure can provide consistency when identifying priorities for action, highlighting both spatial and temporal interactions of risk exposure with intrinsic vulnerability, together with the scope for adaptation to moderate these risk factors [10,11]. Risk framing is also consistent with emerging concepts of safe planetary operating boundaries, presently identified at greatest risk for biosphere integrity, biogeochemical (nutrient) flows, and climate stability [12].

Risk assessment for climate change has by necessity to differ from conventional risk assessment that uses quantification of standard risk factors to evaluate risk severity [11]. Variations in available climate change evidence and requirements to track spatially-varying risk factors from present to future, imply a need for broader assessment including both qualitative and quantitative analysis. Evidence may include theory, empirical data (site observations, monitoring networks etc.), paleoenvironmental reconstructions, experimental manipulations, computer modelling, and meta-analysis. Multiple independent sources, including from different locations, can therefore be key in establishing general inferences and scientific confidence. Projections of changing future risk levels require extrapolation of risk factors based upon different scenario assumptions, sometimes supported by model simulations. Confidence in the credibility of future projections can therefore be increased if the same techniques can reproduce current or past changes consistent with empirical data. Risk assessment also requires that a consistent framework and logic for risk assessment is maintained across diverse evidence sources and academic disciplines [13], hence exploration of an ecosystem approach in the present study.

2. Ecosystem-based Approaches

Ecosystems act as self-organising functional systems that dynamically integrate biotic communities with abiotic processes, and which can mediate exogenous factors, including climate [14]. An ecosystem approach to decision making recognises humans as integral components of ecosystems through coupled socio-ecological systems, thereby combining strategic objectives for biodiversity conservation with those to sustain ecosystem benefits for human welfare, as formally recognised by the United Nations Convention on Biological Diversity and Aichi 2020 Biodiversity Targets [15,16].A unified conceptual framework to advance these objectives is provided through characterisation of 'ecosystem services' relationships. Hence, ecosystem functions, such as nutrient cycling, water cycling, and primary productivity, maintain ecosystem integrity and provide essential benefits to humans through ecosystem services, which may be categorised as provisioning (food, fibre, water etc.), regulating (soil/water/air quality, hazard alleviation, climate stability etc.) and cultural services (amenity/aesthetic value etc.) [17]. 'Natural capital' then defines the cumulative stock of natural assets providing ecosystem services [18].

The utilitarian philosophy of ecosystem services and natural capital has been criticised for its focus on human requirements which overlooks the intrinsic value of nature; but its conceptual advance is a systematic framework providing fresh insights into the sustainability of human-environment interactions, whilst also incorporating diverse stakeholder interests which can be advantageous from a policy perspective [19,20]. Calls for systems approaches in natural resource management have been prompted by increased recognition of indirect effects, as in agri-food systems [21,22]. Agricultural intensification to supply food and fibre has often involved secondary effects that have reduced biodiversity and homogenized ecosystems [23,24]. Impacts include excessive human appropriation of net primary productivity and loss of soil organic matter; use of pesticides that replace natural pest predators; or artificial fertilizers that replace natural nutrient cycling. These side-effects can cause disruption to the self-regulating functions and integrity of ecosystems.

Climate change, combined with other stresses, has potential to further modify ecosystem functioning with consequent risks to ecosystem services [25,26]. However, ecosystem risks to human wellbeing remained understated in climate change assessments. Sectoral assessments have predominantly separated the natural environment from the resources or services provided to people [27,28]. Hence climate risks for biodiversity and soils have usually not been fully followed through to their resultant consequences for agriculture, forestry and water resources, and *vice versa* [29], despite evidence suggesting sectoral issues are significantly modified by cross-sectoral interactions [30]. Recently, some regional and national assessments have begun to use an ecosystem services framework to identify climate change policy priorities, as in Germany [31]. For the US National Assessment, a principle of 'what matters most to people' was used to identify key ecosystem services impacted by climate change [32]. However, the potential added value from using climate change risk assessment with ecosystem services has yet to be fully realised.

3. UK Climate Change Risk Assessment

The first UKCCRA in 2012 provided a comprehensive evaluation of sectoral risks but made less progress on cross-sectoral risks [33]. Hence, the second assessment (UKCCRA2017) received a remit to develop a more unified structure linking biodiversity, agriculture, forestry, and water resources sectors from UKCCRA2012, consistent with government aspirations for a 'whole systems' approach to the natural environment [34]. As part of this process, detailed risks defined for UKCCRA2012 were in some instances grouped together to define a smaller list of risks for UKCCRA2017, including in some cases, potential opportunities. An ecosystem-based approach was adopted by UKCCRA2017 to investigate cross-sectoral risks, following a rationale that ecosystems represent national assets and infrastructure providing multiple societal benefits including climate resilience (Fig. 1). For pragmatic reasons, assessment did not aim to provide detailed analysis of all ecosystem services but rather to use this framework to reference risk relationships and priorities, including uptake of ecosystem-based adaptation as a strategy to manage climate change risk across multiple policy objectives [35,36].

UKCCRA2017 used a common methodology applied across multiple assessment domains [37]. Priorities were defined based upon risk magnitude levels and urgency of adaptation responses required to maintain 'residual risk' (i.e. impacts occurring after adaptation) at a societally-acceptable level. This method was an advance on UKCCCRA2012 which only used risk magnitude for prioritisation [7]. Priorities were assessed based upon: (i) current risk levels including existing adaptation actions; (ii) future risk levels including existing adaptation actions; and (iii) the added benefits from additional actions being taken to address risk in the next five years as a matter of 'urgency'. In addition to near-term risks, the methodology sought to prioritise emerging longer-term risks for which low-regret anticipatory actions implemented now could be strongly beneficial for risk management. These anticipatory actions would include those with long lead times to implementation or those addressing legacy issues causing a 'lock-in' effect leading to increased climate change vulnerability unless 'lock-in' factors were eliminated [37]. Based upon this risk prioritisation, each risk was allocated to one of 4 categories: (i) further policy action required; (ii) research priority, meaning further action is especially contingent on improved knowledge; (iii) sustain current action including full implementation; (iv) 'watch list', meaning to. keep risks under review as new knowledge develops. This methodology aimed to be diagnostic of the most urgent issues requiring action in the next 5 years but not prescriptive regarding the actual action to be taken which remains the prerogative of policymakers.

The natural environment was the largest constituent section of UKCCRA2017 with over 600 evidence sources reviewed and used to prioritise risks based upon present and future conditions [38]. Assessment was also facilitated by evidence from the National Ecosystem Assessment [39,40] and Climate Change Impact Report Cards [41,42]. The primary source for future climate change was the UK Climate Projections 2009 (UKCP09) which indicate an expected transition to warmer conditions with greater incidence of wetter winters and drier summers, albeit with less confidence in summer rainfall projections [43]. Where available, risks were also contextualised against future socioeconomic scenarios for the UK. Assessment included two external reviews by academic, government, industry and non-governmental organisations which provided over 1150 comments on evidence sources and interpretation.

[Figure 1 here]
[Table 1 here]

4. Risk Prioritisation for UK Adaptation Policy

UKCCRA2017 risk prioritisation for the natural environment is summarised in Table 1. This section describes key evidence sources, their interpretation, and the rationale for the risk categorisation in Table 1. Section 5 then considers systemic risk interactions.

a) Risks to terrestrial species, habitats, and ecosystems due to inability to respond to changing climatic conditions
Risks to soil properties and processes from changing climate regimes

These risks are linked through their association with functioning and biodiversity of terrestrial ecosystems. There is strong evidence that climate change is already affecting biodiversity. Shifts in species distributions have been marked by a general northwards movement in response to climatic warming, including some continental European species moving to the UK [41]. Variations in distributional responses between different species and taxa reflect different capacities to disperse and track climate change [44,45,46] together with effects of habitat fragmentation from land-use change on dispersal ability [47]. Comparing movements for well-monitored species (birds and butterflies) with expected shifts from warming shows very few keeping pace with climate change, therefore accumulating a substantial 'climatic debt' [48]. Evidence also shows species movements to higher altitude, although this may be buffered by other local factors (e.g. [49])

Climatic warming has also been signified by changes in species phenology, most notably through earlier spring events, and to a lesser extent, later autumn events [41,50]. Evidence suggests that phenology may be diverging across trophic levels [51] which has implications for potential ecosystem disruption due to phenological mismatch, as in predator-prey relationships [52,53]. There is also some evidence of adaptive changes through evolutionary responses, but these seem mostly unlikely to occur fast enough to keep pace with climate change [54].

At community level, compositional changes have generally been attributed to multiple factors, often with distinct local patterns, notably from climate interacting with land use change or nitrogen enrichment from atmospheric pollution (e.g. [55]). Climate impacts are especially noted for montane vegetation communities due to thermophilization effects and declines in cold-adapted species [56,57]. Natural inertia in many vegetation communities appears to be resisting change due to the influence of dominant species; as climate change progresses, these communities are become increasingly dislocated from their original bioclimate niche, making them more sensitive to disturbance and significant habitat loss [58].

Risks to biodiversity are expected to increase in proportion to the magnitude of climate change [41], although quantification of losses is confounded by multiple influencing factors and high likelihood of non-linear effects [25]. Bioclimate envelope models, ecological modelling, and experimental manipulations suggest major changes in species distribution and community composition, but outcomes will also be dependent on wider biotic and land use interactions, which are often not incorporated [26,59]. Ecosystems at highest risk include montane habitats, due to temperature sensitivity, and those that are especially sensitive to changes in moisture regimes, notably wetlands. If other stresses are reduced, some ecosystems can transition between multiple quasi-stable states, providing natural adaptive capacity (e.g. peatlands [60]).

Climate is a major influence on soil properties (texture, structure, porosity, chemistry, colour) and in the longer term on soil formation. Climate risks are especially manifest through loss of soil biota and organic matter together with structural damage (e.g. compaction and loss of porosity) and increased erosion. Impacts on soil biodiversity occur directly through changes in temperature and moisture, and indirectly through shifts in resource supply from plants, leading to changes in the diversity, composition and functioning of soil communities [61]. Interactions with above-ground communities can influence nutrient and water cycling, greenhouse gas emissions, and leaching of nutrients to water bodies.

Soils are exposed to multiple stresses, with land use usually the dominant stress [62,63], hence large-scale direct evidence of climate change is difficult to attribute. For example, a recent European multi-site study showed that intensive agriculture reduced soil biodiversity, making soil food webs less diverse with fewer functional groups [24]. Analysis suggesting climate change as a key driver for recent declines in soil organic carbon (SOC) [64] has been contested and instead primarily attributed to agricultural intensification except in semi-natural uplands where climate change influences seem clearer [65]. Similarly, although local evidence exists for increased climate-related soil erosion and compaction, large-scale trends are masked by land-use drivers [66]. Future projections suggest risk will increase with greater magnitudes of climate change, but with geographic variations as climate interacts with soil type and land use system. In the UK, water erosion and compaction are more likely to increase in wetter areas of the north and west, with aridity and potential increased wind erosion as increasing risks in the south and east. Projected SOC changes have high uncertainty: a warming climate will cause loss of SOC through increased soil respiration rates but may be counteracted by SOC gained from enhanced plant growth; other influencing factors include changes in CO_2, moisture regimes, nitrogen deposition and land use [67].

Using UKCCRA2017 methodology, risks to terrestrial ecosystems, and to soils, were both identified as priorities for action. Climate change impacts are already evident for some species and habitats, and expected to significantly increase in future, with major policy implications for meeting nature conservation objectives. For soils, climate change impacts are less clear, but expected to significantly increase in future in combination with other stresses, especially by affecting the slower pedological processes determining soil properties. Risk prioritisation is also justified through the integral role of biodiversity and soil processes in healthy ecosystem functioning, and therefore in managing other UKCCRA2017 risks defined in Table 1 through ecosystem service relationships, including: natural carbon stores; soil fertility for agriculture and forestry; regulation and purification of water resources; and cultural benefits from landscapes. Ecosystem complexity means that adaptation measures to enhance climate resilience necessarily have long implementation times, hence action needs to become operational now to reduce existing pressures and build adaptive capacity. Evidence has also identified practical barriers to implementation of adaptation plans that need counteractive measures [68]. Current strategies for biodiversity conservation are strongly founded on protected areas where favourable condition can be maintained through sympathetic land management. However, there is recognition that favourable conditions need to be extended over a larger area with enhanced ecological connectivity to address current problems with habitat fragmentation [69]. This will require cross-sectoral co-ordination and engagement with diverse stakeholders, also lengthening implementation times. Policy to maintain soil quality is underdeveloped both internationally, and in the UK, hence urgent actions are needed to address current pressures from degraded structure, loss of organic content, and loss of nutrients, and to restore natural resilience [70].

Understanding effectiveness of alternative adaptation strategies requires supporting research, including on ecological networks, climate refugia, and the design of protected areas, in the context of both macro- to micro-climate level effects, and non-climate influences on species, habitats and ecosystems. Improved understanding of ecosystem function and resilience also remains crucial for assessing ecosystem services implications. Species diversity has been established to have a key role in stable ecosystem functioning [71,72], but the effects of changes in community structure remain poorly understood. This knowledge deficit is associated with limited information on functional roles of many species [73] and the relative influence of genetic, species and functional diversity compared to extrinsic factors (e.g. soil fertility and structure) in driving ecosystem processes, particularly for soil invertebrates and microorganisms [61]. If functional relationships are confirmed as context-specific with significant spatial and temporal variations [74], this will highlight the need for further tailoring of adaptation actions to local contexts.

b) Risks to freshwater species, habitats, and ecosystems from changing hydroclimatic regimes

Freshwater ecosystems are at risk of disruption from changing hydrology and thermal regime. At present, a climate-related long-term UK trend in the composition and functioning of freshwater ecosystems, or in the quality and quantity of water resources, can only be attributed with limited confidence [42]. Difficulties in attribution occur both due to natural climate variability and changes in non-climate drivers over recent decades, notably land use, atmospheric pollutants and channel modification. Interactions have pronounced spatial variation and because much of the relevant research is at local scale and involves short time series, caution needs to be applied in deriving general inferences [75]. Inter-annual and inter-decadal variability is a key feature of hydroclimatic phenomena in NW Europe, particularly associated with shifting modes of the North Atlantic Oscillation (NAO), influencing precipitation, soil moisture, snow-melt, river flows, groundwater storage and thermal regime [76]. These variations can also be detected in functioning of aquatic ecosystems and in water quantity and quality measurements, meaning that trend assessments can be sensitive to analysis period [42,77].

Since the 1960s, UK winter stream flows have increased in upland western areas and autumn flows have increased across much of the country, resulting in increased high flow magnitudes and durations [78,79]. However, limited longer-term records means trends are easier to explain in terms of interdecadal shifts between 'flood rich' and 'flood poor' periods rather than a sustained increase in high flows [79,80]. Recent innovation in large-scale data pooling at European level shows changing 1960-2010 patterns of high flow seasonality due to temporal shifts in maximum soil moisture (W Europe) and storm incidence (N Europe) [81]. Interpretations of UK spring and summer flows (including low flows) and for groundwater are generally more inconclusive [78,82]. For river temperatures, analysis over a recent 17-year period shows average increases of 0.03°Cyr^{-1} [83] but again longer-term trends remain less clear [84].

Climate-related trends in aquatic ecosystems are most clearly detected at locations less affected by other pressures [85], and particularly signified by decline of cold-adapted fish and invertebrates [86,87,88]. Warmer water can increase chemical reactions, bacteriological processes, growth rates of algae and plants, and affect the life cycle and physiology of fish and invertebrates. Climate sensitivity is demonstrated by phenological changes, which also show variations across trophic levels [53]. Future projections suggest that warming will cause significant modifications to seasonal functioning of rivers and other water bodies [89,90]. Deoxygenation from increased incidence of low flows and reduced water levels, together with stress to species from higher water temperatures, would significantly increase risk of ecosystem disruption, exacerbated by reduced dilution of harmful pollutants and further deoxygenation from increased incidence of algal blooms. Risks are highest during drought episodes, but future projections of increased drought severity have limited confidence [91].

Although current trends often remain inconclusive, there is strong evidence for climate sensitivity in freshwater systems, particularly during extreme events, and future climate projections imply increased risk exposure as hydrothermal regimes are altered. Policy development through the EU Water Framework Directive (WFD) recognises 'good ecological status' (GES) as a key characteristic of functioning, resilient water bodies. However, many water bodies do not currently meet GES and are sensitive to further ecological stress [92]. Pollution from point source discharges and toxic substances has decreased in recent decades but nutrient levels in many UK catchments have increased, mainly related to land-use intensification and increased fertilizer application [93,94]. Increased frequency of heavy rainfall events would therefore exacerbate risks to water quality due to runoff of farmland pollutants and dissolved organic carbon from degraded peatlands.

Working through the UKCCRA2017 methodology has led to a policy recommendation that current actions through the EU WFD are sustained through continued efforts to establish GES and provide minimum ('environmental') flows for healthy river ecosystems. Evidence does suggest additional adaptation measures will be required as climate change intensifies but these will need to be matched with river basin contexts [95]. Hence, this risk topic is identified as a priority for further research to guide appropriate adaptation options (Table 1) by analysing multiple stressors and effects of changing climate variability, seasonality, and extreme flows on water quantity, water quality, and ecosystem processes [96]. For example, there is a need for improved knowledge on effectiveness of riparian vegetation shading in averting extreme water temperatures and the robust setting of environmental flows to avoid ecological stress.

c) Risks/opportunities from changes in agricultural/forest productivity and land suitability

The productive capacity of land to provide food and fibre through agriculture and forestry is influenced by climate and other biophysical factors, including soil properties and topography, acting in combination with socioeconomic factors. Changes in key bioclimate variables (growing season, soil moisture, frost risk, wind exposure etc.) can therefore be instrumental in choice of crops, livestock or tree species, presenting both risks and opportunities. National land use policy may be facilitated through categorisation of biophysical factors into land suitability or capability classifications, with a rationale that land is a finite resource requiring strategic planning and protection [97,98]. However, actual land use patterns are also influenced by socioeconomic processes through market prices, local traditions, and individual preferences.

In the UK, recent decades have been marked by longer growing seasons and decreased frost incidence providing opportunities to improve productivity [97,98]. However, geographic variations in precipitation patterns have produced contrasting differences in seasonal soil moisture fluctuations. Northern and western UK regions are more constrained by soil wetness factors, with some areas becoming wetter in recent decades [99], whilst some drier eastern and southern regions have encountered increased soil drought risk [98]. Wetter soils impose restrictions on machinery use and livestock numbers, whilst drought-prone soils can reduce productivity unless irrigation is available.

Climate change is currently difficult to detect in UK crop yield data due to other dominant factors (notably new technology and crop varieties), however, climate sensitivity is shown by correlation of 'poor' weather years (especially wetter summers) with reduced crop yields [100,101]. Increased inter-annual variability in wheat and potato yields also appears related to increased variability of bioclimate factors, possibly due to current crop varieties being optimised for 'good' weather years [102]. Similar findings are evident for livestock production with climate sensitivity more apparent during extreme years in sensitive locations, notably marginal uplands at limits of agricultural viability [103]. For forestry production, the main risks are currently damage from pests and diseases, and windstorm damage, but a clear climate-related trend has not been detected [104]. Longer growing seasons and increased atmospheric CO_2 concentration may be influencing increased tree growth but this trend is also associated with enhanced atmospheric N deposition [105].

Future climate projections imply changing geographic patterns of risk and opportunity, which could be incorporated into national land capability planning. However, existing research is based upon assumptions derived from existing land management practices and requires further validation to incorporate adaptive capacity of different land uses (e.g. new crop varieties). For this reason, evaluation of land capability to meet changing future demands has been defined as a research priority (Table 1). Advantages of climatic warming are likely to provide relative opportunities in northern UK areas that are currently limited by shorter growing seasons or soil wetness [97]. However, increased prevalence of drier summers will exacerbate water availability constraints in eastern England [106] and may extend water constraints to eastern Scotland [107]. In addition, wetter winters could increase problems with waterlogged soils, especially for locations with limited soil permeability, counteracting advantages from a longer growing season [99]. More land is also expected to be at future risk from flooding, especially on fluvial floodplains where alluvial soils currently provide good quality farmland, and in the coastal zone due to sea level rise (section 4e) [108]. Future scenarios suggest different combinations of climate change, socioeconomic drivers and policy priorities can lead to rather divergent pathways for land use and this has implications not only for food production but also for biodiversity, soil, and water resources (e.g. [109,110]).

Crop modelling indicates future decline of potato and oilseed rape yields in the southeast UK but potential increases in the north [111,112], whilst barley models indicate larger yield increases in the west [113]. Opportunities also exist for increased wheat yields, with heat stress identified as the primary threat rather than drought [114]. Geographic changes in land suitability imply that the distribution of cropping systems will shift as an adaptive response [115]. For livestock farming, milder winters and a longer growing season mean a reduction in cold-related stresses and enhanced production of grass and other forages, but winter soil wetness could restrict outdoor stocking whilst summers may elevate risks from heat stress and water availability [116]. In forestry, cooler and wetter upland areas are likely to experience improved growth of many tree species, whilst drier warmer lowland areas incur reduced growth from soil water reductions, particularly on lighter soils [117]. Influence of changing climate variability on crop yields and on relative viability of land uses remains an important knowledge gap. Initiatives to enhance crop yields, including new genotypes and ideotypes, have long lead times, especially with a concomitant need to address pressures on water resources, soils, and biodiversity. Further research is also required on risks to fodder crops, permanent pastures, and their interactions with animal productivity in livestock farming, and on the suitability of new tree species and their provenances in forestry.

Improved understanding of risk in the context of land productivity and food security requires improved knowledge on current levels of adaptive capacity and the strategies adopted by land managers to address changes in risk and opportunity [118]. Current evidence is often site-specific, rather than being representative at national scale, and suggests that responses in agriculture tend to be predominantly short-term and reactive, especially following extreme adverse weather [119], which may increase the potential for maladaptation (section 4d). Poor management can lead to reduced soil quality, land degradation, and limitations on land use options [120]. By contrast, in forestry, lengthy times for tree maturity mean that planned adaptation strategies are evident, but level of uptake of adaptation initiatives remains to be established.

d) Risks to natural environment and land use from water scarcity or flooding
Risks of maladaptive land management practices exacerbating water-related risks and flooding

These risks stem from indirect interaction between terrestrial or freshwater ecosystems and land use regarding excess water or water deficits, particularly in extreme situations. The general west-east UK precipitation gradient means that flood risk is more often a problem in the west whilst water scarcity is more prevalent in the east, although both risk types can occur sporadically in any region [79]. Local factors also influence climate-related risk: soils and vegetation filter, purify and regulate water flows, hence mediating extremes, but these ecosystem services can be disrupted through intensive land use which reduces rainfall interception, infiltration, and soil water storage, and increases surface runoff [121]. The effects of flooding can therefore be propagated to downstream areas whilst sediment and nutrient runoff can affect water quality. For water scarcity, increased irrigation demand to maintain agricultural production can cause conflicts with water requirements both for terrestrial ecosystems and to maintain environmental flows for freshwater ecosystems. Land use intensification also affects the resilience of soil food webs to drought, affecting ecosystem functioning [122].

Projected trends to wetter winters and drier summers in the UK suggest that these indirect risks will increase and they have been identified as a priority for further action. Risks intersect multiple policy domains and there is currently limited coherence between policy objectives for land use, water resources, flooding, and nature conservation, which acts to constrain co-ordinated adaptation planning [123], especially between objectives for agricultural productivity and other ecosystem services. Urgency of response is also associated with a need to amend the legacy of land management responses in sensitive areas that have increased runoff and flood risk, as well as drought susceptibility, and pollution risks to water resources. Proactive land management can moderate risks, including maintaining good soil structure, use of crop rotations, afforestation, floodplain or wetland restoration, or using other natural habitats, to maintain ecosystem resilience and water regulation services. Additional policy support is therefore required to support management actions that restore natural processes (water retention, filtration etc.) that enhance climate resilience, particularly during extreme events. Increased water scarcity risks require strategic interventions to implement sustainable abstraction limits and provide incentives for increased irrigation efficiency [124]. For wetness and flood risk, field drains have been used to maintain productivity, but design and maintenance issues mean reduced efficacy in extreme conditions [99] and they may exacerbate flood risk downstream [125]. Recent flood events have increased policy interest in risk management through natural flood management, but present schemes are generally small-scale initiatives whilst research identifies a need for larger-scale adaptation to be delivered through integrated catchment management to avoid inadvertent trade-offs with other land use objectives [125,126,127]. Policy action therefore requires complementary research to better understand catchment-scale interactions between land use and climate change, and hence combined scope and viability of different adaptation measures for water quality, natural flood management and drought risk [127,128].

e) Risks to coastal ecosystems, agricultural land, and heritage from sea-level rise; and loss of natural protection

High exposure to sea level rise, combined with existing vulnerabilities, mean coastal areas are generally identified at high risk from climate change [129]. A recent accelerated rate of global sea level rise has been detected [130] although evidence for regional trends is complicated by decadal variability [131]. Sea-level rise increases the probability of extreme water levels occurring in association with storm surge events or large waves. Risk exposure is also influenced by local patterns of land uplift or subsidence; in the UK, geomorphological and ecological evidence suggests that relative sea level rise is now ubiquitous, including northern coasts where postglacial isostatic land uplift was previously dominant [132].

Coastal zones contain a functionally inter-related mosaic of ecosystems and landforms that buffer marine incursion. For example, on barrier-type coasts a natural ridge (barrier) reduces wave energy on the nearshore or foreshore and limits inundation of the backshore and hinterland. Similarly, a 10-20m width of saltmarsh has been modelled to attenuate up to 50% of wave energy, with vegetation also protecting substrates from erosion [133,134]. Natural benefits of wave attenuation in terms of reduced loading on coastal defences, has been valued at £3.1–£33.2 billion for England [135]. Coastal ecosystems can also trap and accrete sediment providing an additional buffer against sea-level rise. Sedimentation rates up to 9mmyr^{-1} have been recorded [136] although rates are usually much lower due to reduced sediment availability. Similarly, seagrass beds can actively capture and stabilise sediment, but they are often in poor condition due to excessive turbidity and nutrient loading [137].

The natural response to hydrodynamic forcing associated with sea-level rise would be coastal reconfiguration and ecosystem reorganisation as inundation frequencies, salinity levels, and sediment movements are modified. However, coasts are also usually important zones for human activities and natural responses are often constrained by hard coastal defence structures built to protect settlements and productive land from flooding and erosion. Defence structures prevent inland migration of coastal ecosystems as a natural response to sea-level rise causing intertidal habitats to become 'squeezed' on the seaward side of defences where increased inundation and wave or tidal energy reduce available adaptation space and cause erosion [138]. For example, locations on the south coast of England lost ca.50% saltmarsh area between 1971-2001 [139]. Defences have also disrupted sediment movement from longshore drift which can inadvertently increase erosion and flood risk further along coasts, and restrict natural coastal reconfiguration [140]. Erosion has also caused steepening nearshore profiles which is further increasing wave loading on defence structures [141].

Although future projections for sea-level rise span a wide range, at minimum they imply present increases will continue which, combined with existing vulnerabilities, means residual risk will rise. Beyond this, higher sea-level rise projections imply significantly increased residual risk and raise the likelihood of non-linear responses incurred from loss of natural buffering [135,142]. Coastal barrier features become increasingly sensitive to breaching during extreme high-water events, possibly leading to severe flooding [143]. Risk may be further exacerbated by increased extreme water levels from waves, tides or storm surges, as models suggest for N Europe [144]. Increased frequency of winter 2013/2014 conditions, as marked by a sustained and vigorous Atlantic regime for NW Europe, would have further implications due to increased erosion during such phases [145].

The expected increase in residual risk for the UK coastline has led to this being defined as a priority risk requiring further action (Table 1). Long timescales are required to co-ordinate effective coastal adaptation responses across multiple organisations to reduce risk. Actions also need to redress the 'lock-in' effect of previous management decisions predicated on a static coastline that have reduced natural resilience through restricted adaptation space and reduced sediment supply. In the UK, these strategic challenges are recognised by Shoreline Management Plans (SMPs) which identify region-scale interdependencies through littoral sediment cells, providing a sound basis for adaptation planning [146]. Locally, managed realignment schemes can provide coastal adaptation space for natural processes by moving defence lines inland. However, at local level there is often considerable opposition to realignment meaning a "hold the line" outlook usually dominates in practice [147,148] and managed realignment schemes only occupy a small fraction of the defended UK coast [149]. Although larger-scale interventions are necessary to manage risk, they raise difficult issues regarding availability of compensatory land to allow for marine incursion, including new locations for terrestrial and freshwater habitats. Furthermore, complexity of coastal processes combined with climate change uncertainty means specific outcomes cannot be guaranteed, requiring some flexibility through adaptive management [150,151]. For example, realignment can modify tidal flow in estuaries causing unexpected intertidal erosion [152] or changes in salinity regimes [153]. Process modelling studies are usually not developed at the strategic scale of coastal decision-making; hence, advances in both systems conceptualisation and modelling are required to better inform adaptation outcomes associated with different magnitudes of sea level rise and hydrodynamic forcing (waves, tidal, surge) [129,154].

f) Risks to natural carbon stores

As identified above (section 4a), climate change brings additional threats to natural carbon stores and sequestration processes in soils and vegetation. The consequent risk of increased greenhouse gas emissions may also negatively affect climate change mitigation plans. The rationale for defining this topic as a distinct priority risk for action was to promote a more coherent UK policy process integrating both mitigation and adaptation responses. At present, land-based mitigation actions designed to reduce emissions do not usually consider risks from a changing climate, meaning they may become less effective in future [149]. Climate policy integration therefore requires that emission-reduction schemes are also 'future-proofed' for spatiotemporal variations in risk (or opportunity) associated with a warming climate, including variations in all bioclimate parameters that influence the carbon cycle and primary productivity (e.g. soil moisture). Implementation of combined mitigation-adaptation schemes are likely to have long lead times due to the path dependency in many land use systems. Maximising long-term carbon storage benefits becomes especially important when identifying locations to restore or enhance peatlands and other carbon-rich soils, and the most suitable locations and species for afforestation [149].

f) Risks from pests, pathogens & invasive species

Climate change modifies risk factors associated with pests, pathogens, or invasive species, depending on their individual characteristics. Existing evidence shows changing geographic distributions and seasonal timing of outbreaks, with strong indications of further shifts from climate change that will affect agriculture, forestry and nature conservation objectives [112,155,156]. Risks are often attributed to increased incidence of milder winters and reductions in ground frosts that kill nuisance species but may be exacerbated by loss of natural predators or competitors in simplified ecosystems [157,158,159]. Existing policy measures already include monitoring and risk management for biosecurity, although for invasives this would benefit from further standardisation in the context of ecosystem services [160]. UKCCRA2017 therefore recommended current actions are sustained, together with efforts to enhance international surveillance [e.g. 161].

g) Opportunities from new species colonisations

Climate change also brings potential biodiversity benefits from new species. Evidence suggests protected areas may be conducive to species colonisations [162] but as previously described (section 4a) habitat constraints in the wider landscape mean that colonisation potential is restricted, and the biodiversity and ecosystem benefits are unlikely to be fully realised. This issue was therefore defined as a priority for further action, by incorporating new species opportunities together with existing species risks (section 4a) into biodiversity strategies, requiring reappraisal of management objectives to recognise changing species distributions and site-level viability. However, progress may also require addressing underlying ethical issues, notably regarding definitions of 'natural' or 'native' species, in the context of long-term change and transitions towards ecosystems that contain novel assemblages of species compared to the past [163].

h) Risks from wildfire

Wildfire risks include threats to human life and the natural environment, with associated consequences for land use, carbon stocks, water resources, property and livelihoods. Although large wildfires are infrequent in the UK compared to many other countries, awareness of risk factors are increasing, and these are included within risk contingency planning. Future projections suggest an increase in hot or dry conditions that may trigger wildfires, but studies have not currently detected an increased climate-related incidence of UK wildfires [164,165,166], despite apparent trends in other countries. Application of UKCCRA2017 methodology therefore leads to a recommendation that current actions be sustained and reviewed against any new evidence in the next assessment.

i) Risks to amenity, heritage & character

Landscape change has important implications for social and cultural benefits derived from the natural environment. Although recent research on cultural ecosystem services has increased awareness of such intangible benefits (e.g. [167,168]), the influence of climate change remains rather uncertain. Most notably, evidence remains limited on how people perceive landscape changes (e.g. in vegetation or land use patterns), and their effects on culture, identity, or other aspects of wellbeing. This topic is therefore an example of an issue placed on the UKCCRA2017 'watch list'. For example, research methodologies are now investigating the role of landscape features in climate change risk perception [169]or using scenario visualisation techniques to elicit diverse responses on landscape change [170,171].

5. Systemic Risks

Climate risks may propagate from an initial direct impact to affect a wider system, possibly exacerbated by uncoordinated reactions and sectoral conflicts [27,172]. Consistent with similar findings at European level [4], UKCCRA2017 highlighted indirect climate risks to the natural environment from land-use interactions (section 4d), particularly when triggered by extreme events such as flooding and drought. Current evidence therefore suggests that land management decisions are a pivotal factor in systemic risks, although knowledge of indirect risks remains constrained due to limited information on combined adaptive responses across land-use systems. In sensitive locations, evidence suggests indirect impacts from combined land use and climate change can exceed direct climate effects [30,109,110]. This is because land-use decisions are influenced by weather and climate in combination with socioeconomic factors, hence responses can be influenced by a variety of non-climate contextual issues including legacy factors, whilst these decisions also act to indirectly affect risk outcomes for biodiversity, soils, water resources, and coastal areas.

Across diverse socio-ecological systems, climate change increases the risk of detrimental trade-offs between different ecosystem services [173]. These trade-offs are shown to be greater in scenarios where provisioning services to supply food, fibre and water are prioritised at the expense of regulating services that maintain soil and water quality, and protection against flooding and erosion hazards [173,174]. As finite resources, soil, land and water are susceptible to imbalances of availability compared to demand, with over-demand leading to increased competition and potential overexploitation of resources. Evidence used in UKCCRA2017 highlighted that climate change will affect not only the quantity of these resources but also their quality.

Although potential for crop yield gains through sustainable intensification and resultant agricultural 'land sparing' schemes have been suggested as strategies to avoid ecosystem service trade-offs, such strategies are challenged by both socioeconomic factors [175] and climatic risks [115]. In reality, geographic shifts in cropping and livestock systems will very likely be required to sustain production and meet demand [115]. Such geographic shifts, either by planned or reactive responses, will have major implications for biodiversity, soil, and water, which in turn may then act to constrain future land use options unless precautionary measures are adopted to avoid land degradation [120].

The scale of systemic risk from interactions between the natural environment and people therefore remains a major unknown but will be strongly influenced by the magnitude of climate change in combination with socioeconomic drivers and policy priorities. Risk may affect geographic flows of natural capital that sustain human welfare at region, national or international scales [4,28]. This includes disruption to the supply of food, fibre and water from rural to urban areas. It also includes disruption to ecosystem services providing natural climate resilience, including downstream benefits of flood alleviation and water purification from upland to lowland areas, or coastal benefits from natural flood and erosion protection. Large-scale flows of natural capital occur to specific regions that already experience stress on water and land resources, notably SE England, suggesting high sensitivity to changing risk factors [176].

6. Recommendations for Future Assessments

Comparisons across several European countries have shown that progress in developing national adaptation policies is closely related to development of the science-policy interface [177]. In the UK, the government response to CCRA2017 has been to accept the scientific characterisation and prioritisation of risks as the basis for the National Adaptation Programme [178]. Hence, in general, the move towards more integration in CCRA2017 may be considered to have engendered a more constructive science-policy interface than occurred through the more fragmented process of CCRA2012 [7]. In addition, the CCRA2017 methodology represented a putative advance by explicitly including existing adaptation responses and thus prioritising risks and adaptation urgency based upon effectiveness of existing adaptation actions relative to risk magnitude. Application of this methodology required information on both the magnitude of risk exposure and the effectiveness of existing adaptations in reducing vulnerabilities or enhancing opportunities, which for the natural environment was not consistently available. In addition, although the risk descriptors used for CCRA2017 (Table 1) were considered more useful than CCRA2012 [7], feedback has suggested more work is required to establish a systematic approach to risk characterisation across sectors that integrates scientific logic and risk communication. Several issues therefore remain for improvement which are used here as a basis to develop recommendations for further assessments.

Firstly, findings from CCRA concur with other studies suggesting that, despite an extensive range of publications associated with climate change and the natural environment, science is not providing enough relevant information for strategic adaptation decision-making [179]. More specifically, a narrow academic focus on localised impact studies is not consistent with policy requirements for evidence from larger-scale and cross-cutting studies on risk dynamics. However, methodological advances suggest there are good prospects for improved interpretation of changes in risk exposure, if applied consistently. New analytical techniques, including data pooling of observations over larger areas or space-for-time substitution (e.g. [65,81]), provide enhanced scope to distinguish climate change from other drivers or contextual factors. Formal attribution procedures [180] or cross-scale frameworks for biodiversity and ecosystem services [181] also provide improved analytical structures. Similarly, there is increased scope for greater use of structured systematic reviews to evaluate contested evidence by comparing results with underlying assumptions [182], as would be advantageous for example for SOC changes. Limitations of general climate change scenarios (e.g. UKCP09) for representing climatic risk factors can also be addressed by development of bioclimatic, hydroclimatic, or agroclimatic metrics (e.g. soil moisture; streamflow indices), and improved integration of observations with future projections, particularly for heterogeneous climates in upland or coastal areas (e.g. [183,184,185]).

Despite improving evidence on risk exposure, UKCCRA2017 found much less information on how existing adaptation responses are moderating risk, and hence on residual risks. Across Europe, only a few countries monitor or report progress on national adaptation strategies, and even fewer evaluate their effectiveness [4,186]. In the UK, the Climate Change Committee now provides formal progress reporting, but adaptation often remains a major knowledge gap (cf. [149]). Although policy may advocate a proactive adaptation strategy, implementation barriers can impede progress, as identified for water management, biodiversity and coastal management [68,123,148]. Available adaptation information also appears biased towards case examples that may not be necessarily representative, such as local pioneer examples of good practice. Most examples of ecosystem-based adaptation, such as through ecological networks, natural flood management, or managed coastal realignment, are currently at local rather than strategic scale. Furthermore, some adaptation actions may apparently reduce short-term risk, but increase longer-term risk [187]. Agriculture appears notably dominated by shorter-term reactive responses; farmers mention difficulties in reconciling current risks with climate change projections (e.g. UKCP09 [119]), but there is a concern they may be forestalling adaptation decisions until a future crisis when options may be further constrained. In addition, there are indications of important differences between farmers' intended and actual behaviour regarding climate change [188].

It is therefore recommended that national surveys to evaluate adaptation in practice become integral to risk assessment, in conjunction with stakeholder engagement. Surveys should consider influence of change and uncertainty on current practices to assess their 'riskiness' in terms of exposure to possible futures that may bring unacceptable risk (e.g. flood management [189]). Evaluation should also consider 'lock-in' effects where risk will inevitably increase due to legacy decisions and current adaptation barriers (e.g. coastal areas [148]). In agriculture, traditional short-term management decisions based upon cost-benefit analysis become challenged when outcomes have long lead times or are irreversible, identifying scope for improved techniques to assess riskiness and adaptability (e.g. real options or robustness [190]). National-scale assessment of risk dynamics would also be facilitated by incorporating different rationales for adaptation (e.g. reactive or anticipatory) into the further development of land-use change scenarios, based upon both climate and socioeconomic drivers.

Current evidence suggests that knowledge of indirect and systemic risks remain an important barrier to further development of cross-sectoral adaptation policy. In UKCCRA2017, risks were referenced according to an ecosystems approach under a headline topic of 'risks to natural capital'. Most participants agreed this provided a more coherent structure for policy development than UKCCRA2012; however, concerns remain, particularly with application of ecosystem services concepts. It is therefore recommended that an ecosystem approach is continued and further elaborated, facilitated by further innovative use of systems thinking to characterise key human-environment linkages and their response to multiple stresses, including techniques to anticipate risks from critical transitions [191]. Currently, knowledge of biophysical and socioeconomic relationships for ecosystem service relationships remains incomplete, often inconsistent, and lacking in quantification, even in the current climate [192,193,194]. Ecosystem services terminology can also be confusing and its incorporation into decision-making remains constrained, usually referencing individual services rather than a holistic framework [31,195]. Based upon these constraints, UKCCRA2017 only provided a limited assessment of ecosystem services for adaptation policy. Scope therefore remains for a more holistic approach to future assessments as evidence matures across the full relationship hierarchy of ecosystem functions and services.

A further recommendation is to consider an expanded role for iterative risk assessment in policy development. Climate change, particularly for the natural environment, involves issues that extend beyond 'objective' procedures assumed for conventional risk assessment, with implications that may challenge prevailing norms or notions of 'acceptable' risk. For example, shifts in species distributions obscure distinctions between 'native' and 'alien' species, and bring an increased likelihood of novel ecosystems, challenging existing ethical and legal foundations for nature conservation [196,197]. Restoration of ecosystems to within their historical range of biotic and abiotic characteristics and processes may therefore not be possible [198]. The goals for environmental conservation, whether framed in terms of species protection, maintaining ecosystem services for people, or a more holistic 'people and nature' philosophy consistent with the ecosystems approach, remain subject to vigorous debate [199]. Similarly, objectives for land use policy are subject to many diverse interpretations and often associated with significant legacy issues [200]. Risk assessment can therefore show that existing policy objectives and their desired outcomes are no longer viable, particularly where objectives aim to maintain the status quo rather than accommodate change. These normative issues have not usually been articulated in climate change assessments to-date yet appear axiomatic in developing evidence-based adaptation policy. Hence, an identified need for risk assessment to become more reflexive and facilitate deliberation of desired outcomes together with status of adaptation initiatives in delivering those outcomes [201]. Particularly for the natural environment, this requires an explicit description of residual (post-adaptation) risk compared to societal notions of 'acceptable' risk, the level of intervention required to deliver desired outcomes, and the influence of irreducible uncertainty on those outcomes.

7. Conclusion

National adaptation policy has a requirement to compare and prioritise climate change risks across multiple sectors. Drawing on findings from the statutory UK CCRA process, this contribution has examined the role of a common risk assessment methodology in shaping policy objectives for the natural environment, integrating evidence from biodiversity, soils, agriculture, forestry, and water resources, together with use of an ecosystem-based framework to investigate risk interactions. Several priority risks were identified which were each associated with an urgency for adaptation actions in the next policy cycle, due to increasing risk magnitude and limitations on existing responses. Loss of biodiversity and reductions in soil quality have important implications for key ecosystem services and human welfare: these were most strongly identified for food and fibre production, loss of natural resilience against flooding and drought, and sustainability of water resources. Limited evidence suggests adaptation is occurring through sectoral initiatives, but in some sectors, notably agriculture, it appears primarily reactive and short-term.

Evidence suggests that risks significantly increase at greater magnitudes of climate change, notably due to limits on adaptive capacity in responding to change. Indirect risk interactions are especially pronounced through the influence of land use change on other risks, with complex systemic risks identified for land and water resources. Requirements for more co-ordinated and multifunctional planning are exemplified by multiple sectoral adaptation initiatives each seeking additional land as space to accommodate change. These sectoral initiatives include: 'space for nature' strategies to increase the area and connectivity of habitats to allow species acclimation or dispersal; 'space for water' strategies to retain water and protect downstream areas from flooding; and coastal managed realignment schemes to reduce flood and erosion risk [69,125,149]. Current planning constraints and implementation barriers mean that opportunities for these initiatives to enhance resilience through ecosystem-based adaptation are limited to small-scale examples.

Key knowledge gaps that currently constrain further development of adaptation policy were also identified, notably for freshwater ecosystems and on the productivity and capability of land to meet future demands for food and other services. Findings also show current knowledge limitations constrain risk quantification, especially for biophysical and socioeconomic interactions that shape indirect and systemic risks through land use and ecosystem services relationships. Addressing these gaps will require further inter-disciplinary research on spatiotemporal variations in risk factors, linking climate and socioeconomic drivers at the strategic scales associated with policy decisions.

Climate change risk assessments also need to improve representation of existing and future adaptation processes (human and natural), and their role in moderating risk levels and building climate resilience. It is therefore suggested that risk assessment may be better framed as a reflexive learning process to better engage with policymakers and practitioners, and to establish the viability of current objectives and the rationale for intervention in the context of sustaining natural processes that enhance climate resilience. Notions of 'acceptable risk' regarding biodiversity and ecosystem services apparently vary depending on individual perceptions of losses and gains, highlighting underlying normative and ethical challenges for defining long-term policy goals. Reflexive integration of risk assessment with adaptation options may therefore help in better defining expected consequences from different courses of action, including the full range of risks they will be exposed to and added effects of uncertainty on the viability of desired outcomes.

Competing Interests

The author declares no competing interests.

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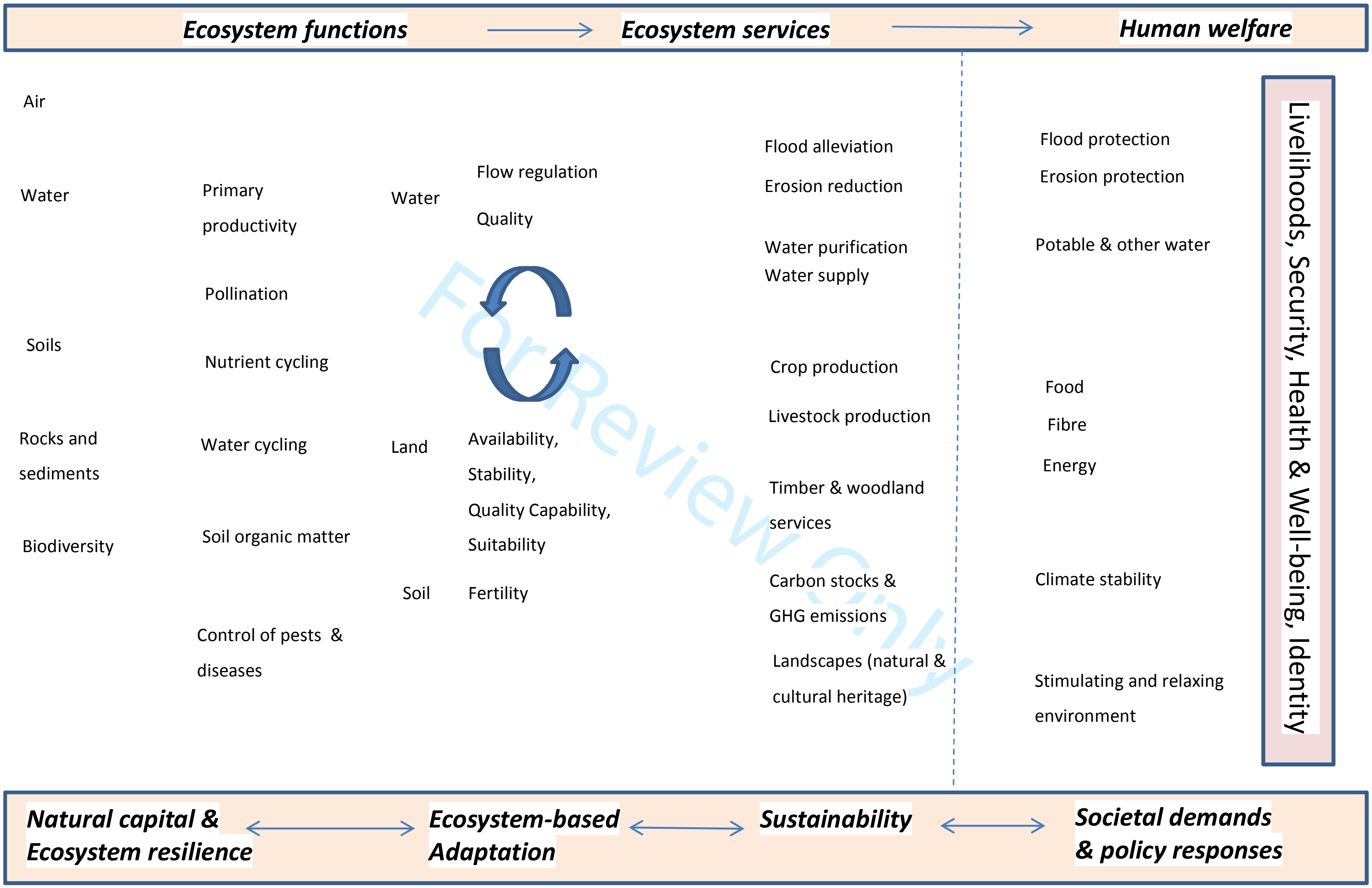
Table 1. Risk prioritisation from UKCCRA 2017

Risk	Urgency	Rationale
Risks to species & habitats due to inability to respond to changing climatic conditions	More action required	Strong evidence of current impacts despite multiple stresses. Risks expected to considerably increase based upon future climate projections and will be exacerbated if other stresses constrain responses. Probable negative impacts on ecosystem functions/services. Policy recognises risk but has long lead times and requires co-ordinated actions across multiple sectors, especially to reduce other stresses and develop landscape-scale adaptation.
Risks to soil properties and processes from changing climate regimes	More action required	Soils already under pressure from multiple stresses. Climate change risks currently difficult to distinguish but likely to significantly increase based on future projections. Probable negative impacts on ecosystem functions/services. Long lead times for adaptation measures to have effect hence urgency of action.
Risks to freshwater species, habitats and ecosystems from changing hydroclimatic regimes	Research priority	Climate change risk currently difficult to distinguish due to shorter-term variability and other stressors. Risk likely to increase based on climate projections. Coherent policy framework established through Water Framework Directive. Further targeted actions require research to identify sensitive ecosystems and implications for catchment ecosystem services.
Risks/opportunities from changes in agricultural/forest productivity and land suitability	Research priority	Combined effect of multiple climate factors and soil properties on land quality and land-use options. Complex spatial and temporal patterns require further validation before incorporation into land use planning and policy to maximise resources at national scale.
Risks to natural environment and land use from water scarcity or flooding	More action required	Risk varies according to distinctive NW/SE geographic pattern but very likely to increase based on future climate projections and socio-economic factors, especially during extreme events. Increased likelihood of conflict between environmental and land use objectives regarding water management requirements. More co-ordinated planning required for land use and water resources.
Risks of maladaptive land management practices exacerbating water-related risks &	More action required	Management practises can degrade soils and ecosystems when attempting to improve productivity, especially in agriculture. Unless guided towards good practice these will act to indirectly exacerbate risk in sensitive regions. Catchment-scale interventions required, notably for natural flood management,

flooding		sustainable abstraction, and raw water quality.
Risks to coastal habitats, agricultural land & heritage from sea-level rise; and loss of natural protection	More action required	Flood/erosion risk already manifest and will increase with further sea-level rise. Policy recognises risk but predominance (and legacy effect) of interventions to maintain a static coastline causes increased long-term vulnerability with loss of ecosystem resilience and natural hazard buffering. More action required to implement strategic-scale shoreline management plans including measures for coastal realignment and functional natural systems.
Risks to natural carbon stores	More action required	Direct climate risks currently have lesser influence compared to land use pressures but very likely to increase with climate warming. Long lead times and expediency of linking adaptation with mitigation measures require co-ordinated actions now, complemented by research to enable spatial targeting.
Risks from pests, pathogens & invasive species	Sustain current action	Existing actions incorporate climate risk awareness, but further research is required to anticipate changing risk factors and to support enhanced surveillance.
Opportunities from new species colonisations	More action required	Currently limited scope to accommodate new beneficial species except in protected areas. Requires reappraisal of conservation objectives and co-ordinated cross-sectoral strategy.
Risks from wildfires	Sustain current action	Risk is sporadic linked to extreme events. No new evidence to infer current change in risk although future climate projections suggest this is likely at some stage. Heat stress issues for crops, livestock and biodiversity require evidence linked to adaptation options.
Risks to amenity, heritage & character	Watch list	Limited knowledge at present although research is increasingly identifying the importance of cultural ecosystem services at local level suggesting important links with adaptation initiatives.

FIGURES

Fig. 1 Ecosystem-based framework for climate change risk assessment (NB in UKCCRA2017, air quality was evaluated with the built environment)


Ecosystem functions
Ecosystem services
Human welfare
Air
Water
Soils
Rocks and sediments
Biodiversity
Primary productivity
Pollination
Nutrient cycling
Water cycling
Soil organic matter
Control of pests & diseases
Water
Flow regulation
Quality
Land
Availability,
Stability,
Quality Capability,
Suitability
Soil
Fertility
Flood alleviation
Erosion reduction
Water purification
Water supply
Crop production
Livestock production
Timber & woodland services
Carbon stocks & GHG emissions
Landscapes (natural & cultural heritage)
Flood protection
Erosion protection
Potable & other water
Food
Fibre
Energy
Climate stability
Stimulating and relaxing environment
Livelihoods, Security, Health & Well-being, Identity
Natural capital & Ecosystem resilience
Ecosystem-based Adaptation
Sustainability
Societal demands & policy responses