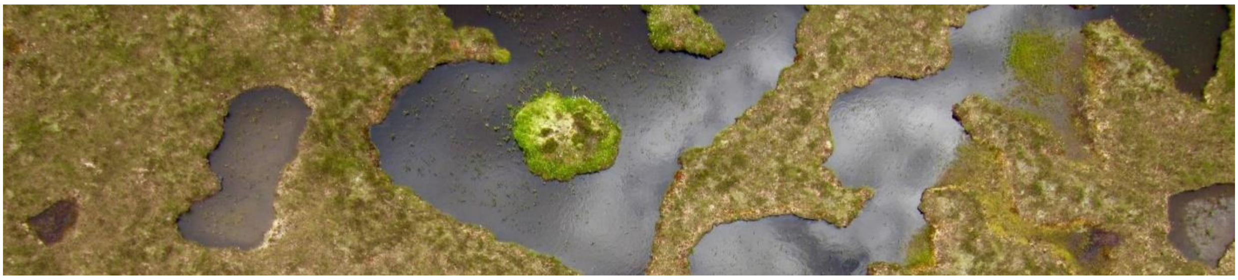
An overview of issues concerning Climate Change Impacts on Scottish Natural Capital.

Deliverable D1.2 for Project JHI-D5-2 'Climate Change Impacts on Natural Capital': A literature review of climate change impacts on Scotland's Natural Capital, mitigation opportunities and associated socio-economic and policy contexts.

30th June 2022



The James Hutton Institute

Acknowledgements: The Climate Change Impacts on Natural Capital Project (JHI-D5-2) is supported by the Scottish Government through the Strategic Research Programme (2022 – 2027).

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Citation: Aitkenhead M, Pakeman R, Gagkas Z, Rivington M (2022) Deliverable D1.2 for Project JHI-D5-2 'Climate Change Impacts on Natural Capital': A literature review of climate change impacts on Scotland's Natural Capital, mitigation opportunities and associated socio-economic and policy contexts.

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Introduction

Purpose of this review is to explore a range of issues concerning climate change impacts on Natural Capital and how assessments of this can be used to inform the development of mitigation and adaptation solutions.

The aim is to not to create an extensive review at this stage, but instead seeks to form the basis for informing discussion on the development of the RESAS Strategic Research Programme Project 'Climate Change Impacts on Natural Capital' (JHI0D5-2) and help set the context for the development of a Risks and Opportunities Assessment Framework. The document also serves to collate information for use in subsequent project outputs.

The objective is to help continue the process to understand the complexity of the impacts of climate change on Natural Capital assets and that options do exist for greater and more impactful mitigation and adaptation within society without significant short-term economic loss. Prioritisation of nature-based solutions within specific landscapes and across specific land uses can be achieved. We also deliberately seek to present challenges on the development of policy and practice, by highlighting a significant body of existing evidence that long-term solutions require researchers and policymakers to openly acknowledge and address the fact that not everyone in society wants the challenges of climate change to be tackled, and that some people are actively working against this agenda.

Role of Natural Capital in supporting society

Natural Capital underpins the ability of the human socio-ecological system to function, through the supply of ecosystem services – our 'life support systems'. By being immersed in, and components of ecosystems, humans have a self-preserving interest in understanding and managing ecosystems as fundamental life-supporting systems. Ecosystems provide the habitat resources needed by species, which in turn regulate key processes. Climate change imposes impacts on species and interactions with physical and chemical properties and processes and hence the functional roles they play in ecosystems. A changing climate therefore alters, directly or indirectly, ecosystem characteristics and the sustainability of life-support services (Munang et al 2010).

This key role of Natural Capital is increasing being recognised within policy development, for example, promoting responsible investment in Scotland's natural assets and associated principles.

Risks to Natural Capital from climate change – The global to Scotland context

The IPCC 6th Assessment Report on climate change (IPCC 2021, IPCC 2022), reports on the degradation of the environment (IPBES 2019) and species extinction (Ceballos et al 2020) make clear that we are on the threshold of a series of compounding conditions and events that threatens the collapse of society. Whilst this may seem an extreme statement to make, the potential for multiple key global ecosystem collapse is increasing:

- Three-quarters of the Amazon rainforest may be moving toward a "tipping point" that, if passed, could leave the world's critical tropical biome a relatively dry savanna within a few decades (Boulton et al 2022). The IPCC 2022 report indicates that the Amazon rainforest ecosystem may collapse by the 2060's.

- The Arctic is warming rapidly, and thawing peatlands and permafrost are a potentially large source of GHG emissions to the atmosphere as frozen carbon is remobilized. Positive feedback from melting Arctic tundra may lead to increasing rates of greenhouse gas emissions (IPCC 2021)

By the 2070’s, the reduction in climate regulation ecosystem services may be to a level of only capture 38% of CO_2 emissions (IPCC 2021).

Role of Natural Capital for climate mitigation and adaptation

Scotland’s Natural Capital assets have both potential to mitigate or exacerbate climate change. Peatlands, as a potential carbon sink or source is a clear example. Peatland restoration has the potential to sequester carbon, but is currently emitting ~4 to 9 Mt CO_2e per year (see Peatland section for more details). However, there are other areas where care is need including woodland expansion, where “the right tree in the right place” and “no trees in the wrong place” is important, as there are a range of things to consider in determining whether carbon gains are to be made or not (Matthews et al 2020, Baggio et al 2022).

It is also important to recognise the relative scales of climate mitigation benefit from the different Natural Capital assets. In terms of the total UK and Scottish carbon footprints, the magnitude of the offset obtained in 30 years if afforestation goals were fully reached would likely be around 1% of the UK total business as usual GHG footprint and around 10% of the Scottish footprint (Baggio et al 2022). Hence whilst there is good potential for Nature Based Solutions to mitigate climate change, reduction of GHG emissions at source still remains the best approach.

Healthy, functioning ecosystems also provide a more reliable basis for adaptation to climate change impacts by land managers working with Natural Capital assets, and society in general (Munang 2010, IPBES 2019).

What can be done to assess risks and opportunities?

A range of tools and approaches already exist that can help support the assessment of the impacts of climate change on Natural Capital, for example flood risk management (e.g. review by Raynard et al 2017), soil water and crop modelling (see below). However, these tend to operate in isolation of one another, at different spatial and temporal scales, and have been designed for different purposes.

NatureScot’s Natural Capital Asset Index has been developed to assess how key assets and their contributions to the national wellbeing are changing over time (McKenna et al 2019, NatureScot 2022), but is not structured (yet) to assess future climate impacts.

Sections below provide some examples of outputs from a range of modelling tools where climate change projections are applied to models simulating things like crop growth, land capability and soil water. There are other examples of application of climate projections to models available. This is an area the project will seek to investigate further and utilise appropriate methods and models.

Part 1: Climate Change Impacts on Natural Capital

There are multiple studies demonstrating how important Natural Capital is for society, and how Natural Capital will be negatively affected by CC. This is an opportunity to flag previously unconsidered issues, not with the purpose of improving the case to SG and society that we need different policies for protecting and enhancing Natural Capital, but instead with the purpose of demonstrating how this can be done without directly confronting the multiple social, political and economic obstacles to any movement away from 'business as usual'. In this review we have worked to identify solutions that circumvent these obstacles, as well as developing further information about specific areas of concern, priority or opportunity.

Summary of climate projections:

The following published key messages on climate projections (UKMO 2019) can be summarised as:

1. Hot summers are expected to become more common. The summer of 2018 was the equal-warmest summer for the UK along with 2006, 2003 and 1976. Climate change has already increased the chance of seeing a summer as hot as 2018 to between 12-25% per year. With future warming, hot summers (like 2018) by mid-century could become even more common, near to 50% more likely.
2. The temperature of hot summer days, by the 2070s, show increases of 3.7 °C to 6.8 °C, under a high emissions scenario, along with an increase in the frequency of hot spells.
    - For the RCP8.5 emissions scenario the estimated probabilistic temperature increase for the UK by 2070 ranges between 0.9 °C to 5.4 °C in summer, and 0.7 °C to 4.2 °C in winter.
3. UKCP18 Global (60km), Regional (12km) and Local (2.2km) scale climate model simulations all project a decrease in soil moisture during summers in the future, consistent with the reduction in summer rainfall and higher temperatures. Locally this could lead to an exacerbation of the severity of hot spells (e.g. reduced evaporative cooling and high levels of heat stress), although large-scale warming and circulation changes are expected to be the primary driver of increases in the occurrence of hot spells.
4. The probabilistic projections (12-member ensemble) provide local low, central and high changes across the UK, corresponding to 10%, 50% and 90% probability levels. These local values can be averaged over the UK to give a range of seasonal average precipitation changes between the 10% and 90% probability levels. By 2070, in the high emission scenario, this range amounts to -47% to +2% in summer, and -1% to +35% in winter (where a negative change indicates less precipitation and a positive change indicates more precipitation).
5. Overall increased drying trends in the future, but increased intensity of heavy summer rainfall events, indicate greater variability and increased frequency of extreme events.
6. Changes in the seasonality of extremes with an extension of the convective season (rising motion of warmer areas of air) from summer into autumn, with significant increases in heavy hourly rainfall intensity in the autumn.
7. Increased intensity of winter storms with higher windspeeds.
8. By the end of the 21st century, lying snow decreases by almost 100% over much of the UK, although smaller decreases are seen over mountainous regions in the north and west.

These projected changes will impact Natural Capital assets by altering the amount, spatial distribution and timing of rainfall and increase surface water loss from evaporation.

Water

The climatic changes and associated changes in temperature and precipitation will likely alter water content in soils and water bodies. Hare et al (2022a) assessed the role of functioning wetlands as buffers against extremes of high and low flow water, finding that Scotland's wetlands are likely to face increased stresses from extremes of droughts and floods. Hare et al (2002b) also provides mapped details of the season shifts projected in a range of climatic variables, indicating seasonal shifts in water availability. The key messages were:

- **The timing of when dry conditions are likely to occur will change.**
  - The month when the maximum drought amount (maximum climatic deficit when evapotranspiration exceeds precipitation) will happen is likely to be later in the year, from currently May towards June in the east and central highlands, but either earlier in the north-west (from June and July towards May-June) or similar to the observed baseline (1994-2014). The month when maximum evapotranspiration occurs was historically in July, and this is estimated to remain in the east, south and north-east of Scotland, but occur later in the year in the west.
  - May has generally been the driest month, but this is estimated to shift to later (June) in the east (reasonable agreement between the climate projections). In the west the driest month is likely to be either similar to the present or later (varied agreement between climate projections).
  - The number of months with successive water deficits is likely to increase, mostly in the east (good agreement between the climate projections) but with some large variation seen between climate projections in the west.
    - This implies dry periods will last for longer.
  - In the observed period July was predominantly the month when the maximum amount of evapotranspiration occurred. There is general agreement between the climate projections that July will continue to be the month with the maximum evapotranspiration rate in the east and central Scotland, but later (August) in the west.
  - There is a variable range of probability of change to the mean length of dry spells. In the central and eastern parts of Scotland it is estimated to increase, but in the west and north-west may decrease.
- **The balance between input precipitation and water returned to the atmosphere from evapotranspiration will change.**
  - Precipitation intensity is likely to increase, but with longer dry spells.
  - Total precipitation input is likely to be spatially and temporally variable.
    - May is estimated to have a variable spatial probability of a decrease in precipitation in the west but an increase in evapotranspiration.
    - There is good agreement between ensemble members that April is likely to be wetter in the west and south, July is likely to be wetter in the north-west, but the north of Scotland will see reduced precipitation in December, and the east will have a decrease in August, September and October.
  - Between 1994-2014, July was the month with the highest evapotranspiration rate across most of Scotland. There is generally good agreement between the climate projections that this will remain the case in the eastern, south-eastern and north-

    eastern parts of Scotland. There is reasonable agreement between ensemble member that in the west and south-west the maximum evapotranspiration will occur earlier in the year.
  - The net effect of changes in precipitation water input and evapotranspiration loss is likely to be less water available in eastern areas, but potentially more in the north-west.
- **The timing of when excess water occurs is likely to change.**
  - There is good agreement between ensemble members in some western and southern parts of Scotland that the excess water will occur earlier in the year, i.e. shifting from December to November.
- **Other meteorological factors are likely to change.**
  - Air temperatures will increase, impacting evapotranspiration rates and formation of surface dews.
  - The length of the growing season will increase. Plants may be able to start growth earlier in the year and continue later into autumn or winter.
  - The rate of thermal time accumulation (determining plant and insect phenology) will increase (growth stages will be reached earlier).
  - There is likely to be a reduction in the number of frost days, with frosts starting later in autumn and ending earlier in spring.
  - The number of days when plants may experience heat stress (i.e. above 25°C) is likely to increase.
  - The number of dry days ($P < 0.2$mm) is likely to increase in the east, potentially to more than 200 days.
  - Snow cover is likely to decrease after c. 2040-2050, changing the balance of water stored and released in upland areas.
  - There is uncertainty about the impacts of climate change on wind speeds and direction, but there is a strong possibility that high wind speeds will increase.
  - Storm intensity will likely increase.
  - Occult precipitation (mist, dew) can be a key source of water input to ecosystems, however, there is uncertainty as to how it will be affected by climate change.

Rivington et al (2020) found that the risks of reduced water availability also extend to Private Water Supplies (PWS), with springs and surface water sources potentially becoming more vulnerable. Snow cover is also expected to decrease substantially during this century, affecting water release from the uplands to streams and rivers, altered surface albedo (micro-climate warming risk) and effectiveness of insulation of vegetation to extreme cold (Rivington et al 2019, Rivington and Spencer 2020).

Soils

Soil Water Balance: The chemical, biological and hydrological functioning of soils will be impacted by the change bought about by climate change in respect of daily soil water balance. Figure 1 shows the estimates from a soil water balance model applied to 477,209 unique soil-climate combinations covering the whole of Scotland, produced using observed period and a future climate projection (UKCP18) (Udugbezi et al 2022). The estimates reflect the availability of water for use by plants.

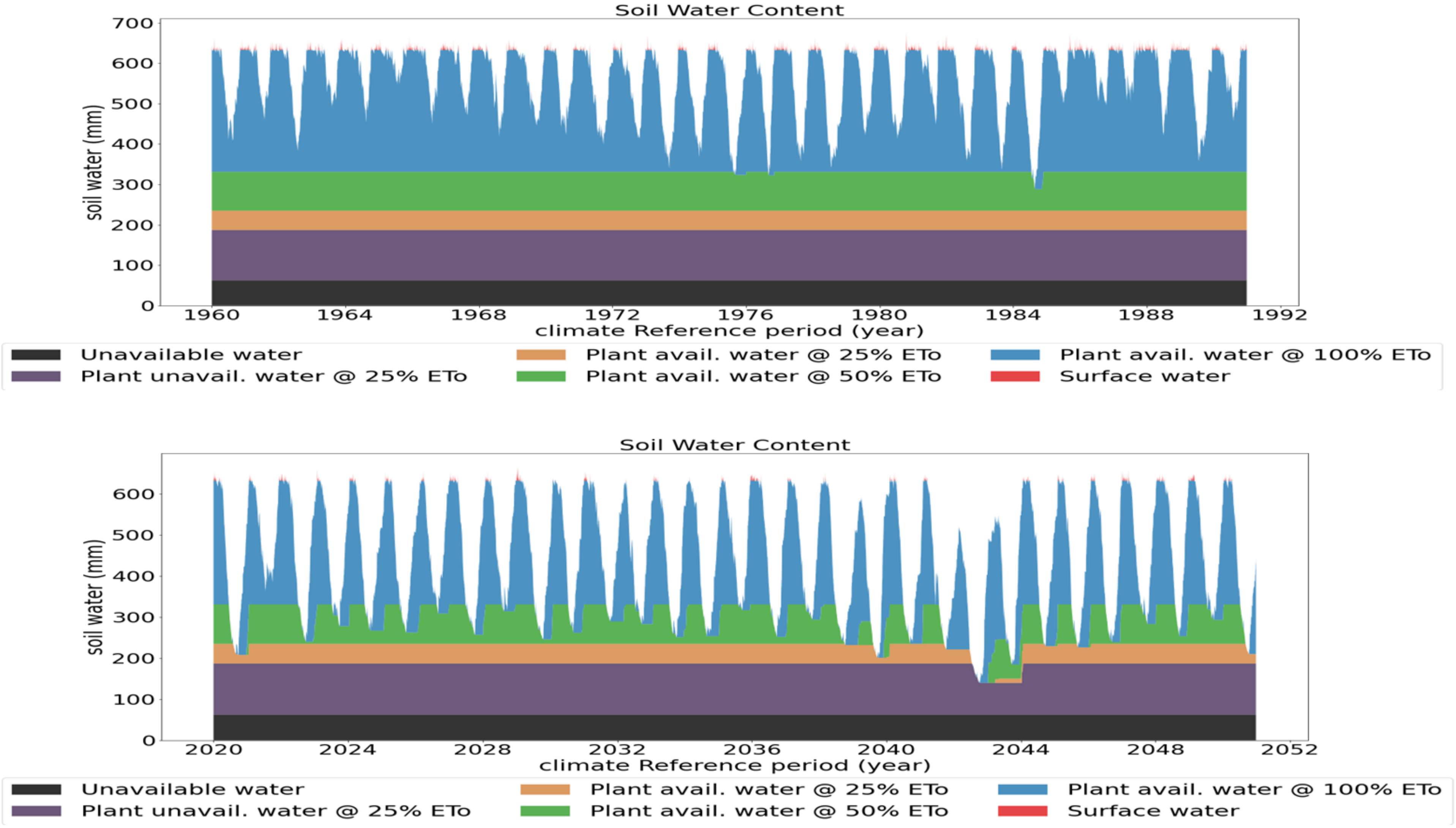


Figure 1. Time series of soil water balance for a Peaty Alluvial Soil (unique ID 104). Top: 1987-2017, Bottom: 2020-2050 for ensemble member 12 (note this is the more extreme projection for the high emissions scenario, RCP8.5). Y axis is soil water (mm), X axis is Year.

The key issues to note from Figure 1 are:

- This is a peaty alluvial soil in near Stranraer, with soil water reaching saturation point every winter (when it can no longer hold any more water and any excess will be runoff, shown in red). As it is an alluvial soil on a floodplain, water table levels are likely to result in the soil remaining wet, especially lower in the profile, however this example illustrates what may happen if water table levels are low.
- There is a greater probability that the soil in the future will become drier and this will happen more frequently. There is more 'white space' on the plots in the future, meaning there is less water within the soil.
- During the baseline period the soil water balance does not decrease to a point where plant water availability is limited whereas in the future projection it does.
    - This may impact on vegetation in terms of changes in growth, invasion of new species and competitiveness between species which can alter how the habitat functions, e.g. as a wetland habitat providing drought and flood buffering ecosystem services.
    - The organic topsoil layer is more likely to become dry, impacting its ability for carbon sequestration, and potentially becoming a carbon dioxide source.
- Not every year in the future projection has excess surface water each winter. In some years the saturation point is not projected to be reached and hence there is a reduced probability of runoff. This may reduce water availability elsewhere in the hydrological system.

The key issues to note from Figure 2 are (following page):

- This is a relatively dry location (near Biggar), where soil water does not reach saturation point in the winter.
- The extent to which the soil dries varies considerably between the baseline period and the near future projection, with the future projection indicating increased probability of more frequent years when the soil may become drier (there is a lot more white space in the wider and deeper 'troughs').
- During the baseline period there are few years (possibly 1984) when crop or vegetation growth on this site may have been limited by water stress (e.g. 1 in 30 years). Under the climate projection, water stress may occur 22 years in 30.

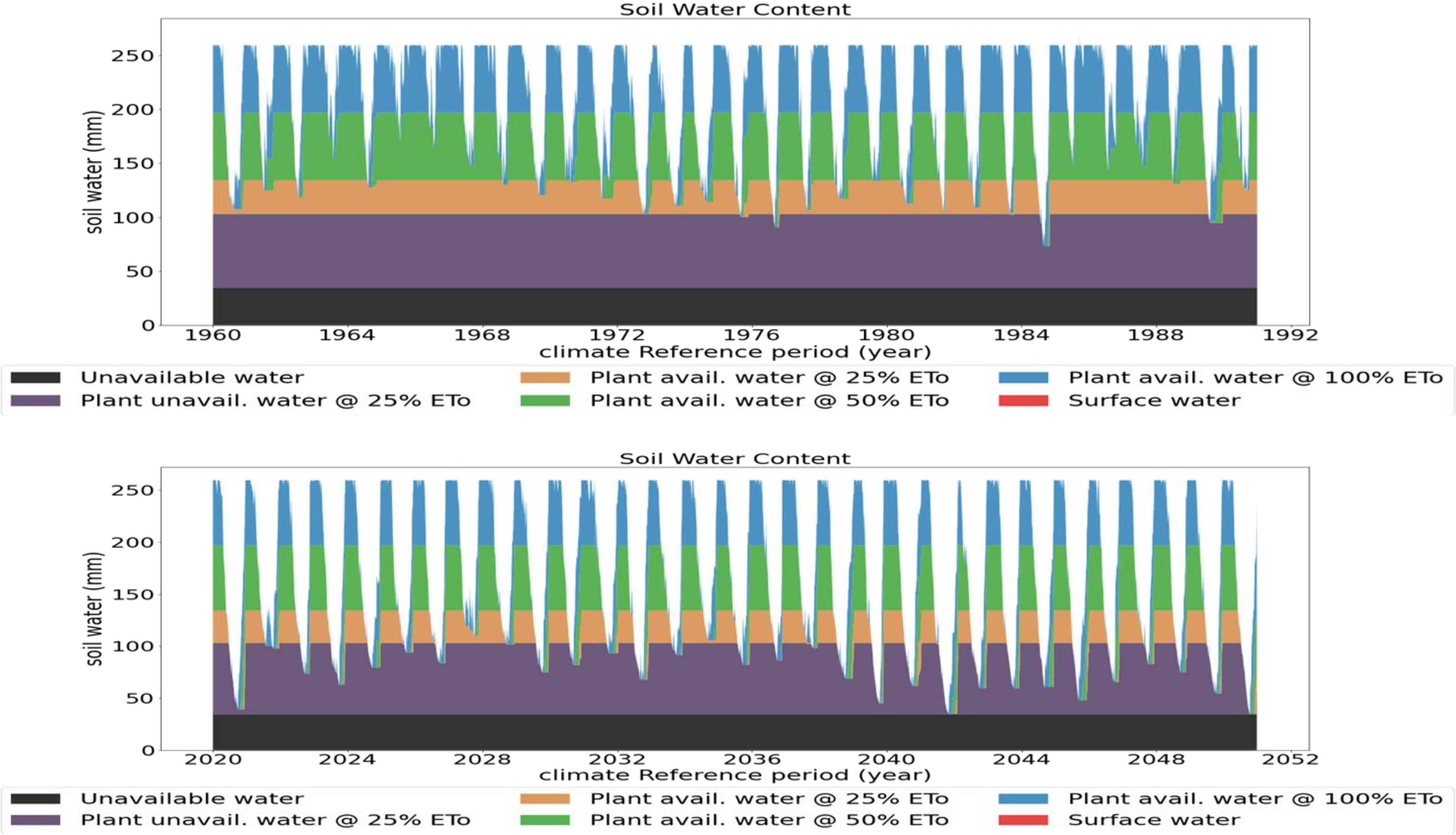


Figure 2. Time series of soil water balance for a Brown Earth Soil. Top: 1960 - 1990, Bottom: 2020-2050 (UKCP18 ensemble member 12, note this is the more extreme projection for the high emissions scenario, RCP8.5).

Soil organic carbon erosion risk will likely increase under climate change (Chappell et al., 2019). In a wider global context, there will likely be increased pressures places on soils due to increasing food production demand to feed almost 10 billion people by 2050. This raises the risk of accelerating soil degradation, releasing even more soil carbon than at current rates. McGuire et al. (2022) highlighted knowledge exchange barriers to improving soil management and the importance of monitoring, reporting and verification in implementing positive interventions. Improved knowledge exchange and reporting on examples of the consequences of not intervening would benefit from solutions in this area and would provide the opportunity to inform policymakers with clear evidence.

Species and Habitats

There remain large uncertainties as to how climate change will impact specific species and habitats and the interactions between them and ability to provide ecosystem services.

It is clear for some groups of species that climate change is already driving an increase in the range of some species in Scotland. This includes groups such as moths (Dennis et al. 2019), and birds (Pettorelli et al. 2019), with both groups having new records for breeding species in recent years. Climate change has also been implicated in the range expansion of invasive species such as the Pacific oyster (King et al. 2021).

Climate change is altering the community composition of ground beetles (Pozsgai et al. 2016) and grassland vegetation (Mitchell et al. 2018) as well as driving large scale shifts in bryophyte occupancy (Pakeman et al, 2019). In contrast, coastal plant communities have so far been relatively resistant to climate change (Pakeman et al. 2015). There are also predictions for range decreases for species including woodland lichens (Ellis & Eaton 2018) and observed and predicted declines in mountain birds (Lehikoinen et al. 2019).

At the habitat level, blanket bogs could be lost from the edge of their current extent as climate changes (Ferretto et al. 2019), whilst climate change could facilitate the expansion of woodland into mountain habitats (Watts & Jump 2022). The extent to which habitats will shift to new types under climate change or just see a re-ordering of species in dominance is unknown and depends upon the likelihood of colonisation by new species into habitats or the presence of potential new ecosystem dominants within a community.

Peatlands

The extent of blanket bog in Scotland is dependent on climate (Ferretto et al. 2019). Changes in climate are likely to reduce this area and by 2050 around half of the carbon stored in peat bogs will be at risk of loss. The size of this loss is between 4.4 and 6.6 times the amount of carbon emitted in Scotland, greatly hampering efforts to meet emissions targets. Blanket bogs are currently a high priority for restoration through the Peatland Action Project (https://www.nature.scot/climate-change/nature-based-solutions/peatland-action-project) with restoration needing to be carried out quickly to derive most benefit (Glenk et al. 2021).

The net GHG emissions contribution from degraded peatlands was~5.8 Mt CO2e per year for Scotland (2019 data that excludes forestry on peat and near-natural sinks), accepting that there are uncertainties (e.g. Matthews 2021) associated with emissions factors and degraded area estimates ranging between ~1.4 to 1.6 million ha,), with ~3,500 Mt carbon at risk from future degradation. Approximately 55,000 to 65,000 ha has been restored since 1990 (with some uncertainty). The long-term apparent rate of carbon accumulation (also with caution being required to interpreting values) is ~0.5 – 1 t ha^{-1} yr^{-1} in the UK, but this can be misleading as it gives the average value of accumulation mass since the start of peatland formation (and hence needs peat dating). The upper layer (acrotelm) can be highly productive, but only a fraction of the new carbon captured by vegetation is sequestered (typically a maximum of 1mm per year). The actual rate requires eddy covariance and other GHG flux measurements balanced by losses (e.g. dissolved and particulate organic carbon) (source: Rebekka Artz's presentation material)

Despite this slow overall accumulation, of particular concern is the potential impacts on key peatland species such as *Sphagnum* sp. (making up a large proportion of the acrotelm), which are vulnerable to desiccation, though the overall response can be complex (Hájek and Vicherová 2013). Loss of primary production from *Sphagnum* will reduce carbon storage if drying occurs and may lead to increased erosion risk and or changes in species composition.

In a review of soil carbon research in Scotland from 2010-2020, Aitkenhead (2021) highlighted several publications identifying the opportunities presented by peat for GHG emission abatement, alongside risks presented to peatlands by climate change. Glenk et al. (2021) highlights the win-win of early peatland restoration as something that the public are willing to pay for in Scotland and where early action will significantly reduce the economic implications of later 'mitigation debt' (i.e the costs of putting off restoration till later). Locations where peatland restoration should be prioritised can be identified using peat depth/carbon stock mapping (e.g. Aitkenhead & Coull, 2019) and mapping of current peatland condition and GHG emission categories (Aitkenhead et al., 2021).

Fire Risks

Climate change has been cited as one of the major influences in increased wildfire occurrence globally (Arnell et al, 2021). Specifically for the UK, mean summer temperatures are anticipated to rise by as much as 2.5°C by 2050 increasing wildfire risk, which can be further exacerbated by potential decreases by over 15% in annual rainfall over the same period (Grau-Andres et al, 2018). Increases in the frequency of drought will most likely lead to more frequent wildfires occurring across the UK, which can be more severe in nature, occur more extensively across landscapes and exhibit more variable seasonality (Albertson et al, 2010; Davies et al, 2013).

Most wildland fires in the UK are usually small in nature - usually under a hectare in size (Arnell et al, 2021) and are most likely to occur in arable, grassland or mountain and heath environments (de Jong et al, 2016, Gazzard et al, 2016). Furthermore, wildfires also occur frequently on remote upland peatland environments (Albertson et al, 2010). Although peatlands may be rare globally, covering roughly 2–3% of the Earth's land surface, between 9% and 15% of Europe's peatlands are located in the UK, with 77% of those occurring in Scotland (Bain et al, 2011).

Wildfires can be destructive for seminatural habitats (Whitehead et al, 2021); they can cause peatland degradation (Carroll et al, 2009; Bain et al, 2011) and reduction of carbon storage; the release of toxic metals into the atmosphere (Turetsky et al, 2006); and extensive damage of sensitive habitats such as Sphagnum vegetation communities (Grant et al, 2012). Overall, it is expected that increased occurrence of wildfires, especially on remote upland area and peatlands, will be costly to fight, cause damage to freshwater catchments and other ecosystem services and require costly restoration (Albertson et al, 2010).

Cropping systems

Changes in water availability, increases in growing season length and other agrometeorological factors are likely to present risks and opportunities for different cropping systems. The response of barley for example shows large spatial variation in yield response due to soil water holding capacity combined with potential shifts in rainfall distribution (Rivington et al 2022). The key findings from this study were:

- With the high emissions scenario used (RCP8.5), climate change is likely to have both positive and negative impacts on barley growth and annual yields, but with an overall decrease in yields by the 2040s, which continues to worsen by the 2070s.
    - It should be noted that there is little difference in estimated climate change between the low and high scenarios until c. 2040 – 2050, after which they start to diverge.
- Under the twelve climate projections used (which leads to temperature increases ranging from 1 to 3.5°C and 7% increase to 14% decrease in growing season precipitation), barley yields are likely to decrease in many parts of Scotland.
    - This will likely be due to additional water stress, especially if water is limited in the spring to early summer periods.
    - Future higher temperatures and potentially reduced precipitation are likely to lead to an increased water deficit, where evapotranspiration loss of water to the atmosphere is greater than the precipitation input to soils.
    - Areas with better soil water holding capacity appear to be more resilient and could potentially experience increases in yield when favourable climatic conditions permit.
- There is good agreement between the climate projections as to where these changes in yield may occur.
- There is likely to be increased annual variability, with some years potentially experiencing good yields when conditions are favourable.
- The spatial extent and temporal frequency of yield decreases is likely to cause substantial challenges to the barley supply chain and end users.
- Earlier sowing appears to be a viable adaptation option.

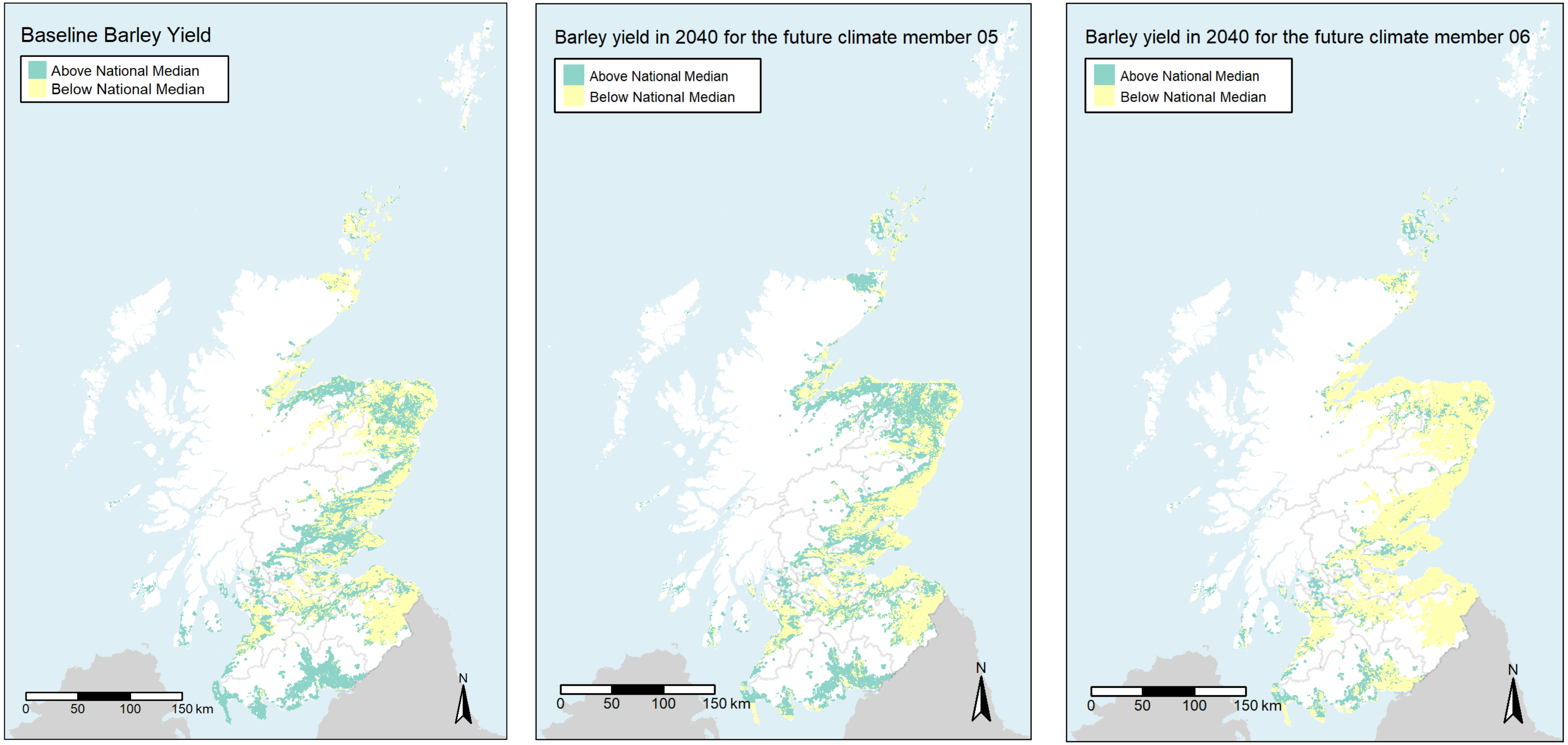


Figure 3. Estimate barley yield responses to climate change: locations where yield is above (green) or below (yellow) the national median yield (6.6 t ha) for the baseline period (1994-2015, left) and two future projections (2040's); little change in precipitation from the historical baseline but 1.8°C warmer (middle); about 8% drier and 1.5°C warmer (right).

The barley modelling study also developed a new approach to communicating uncertainty, through the use of agreement maps (Figure 4). These indicate potential 'hot spots' where yield may change based on multiple climate projections.

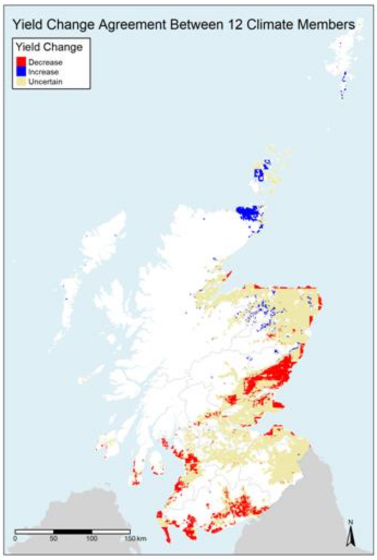
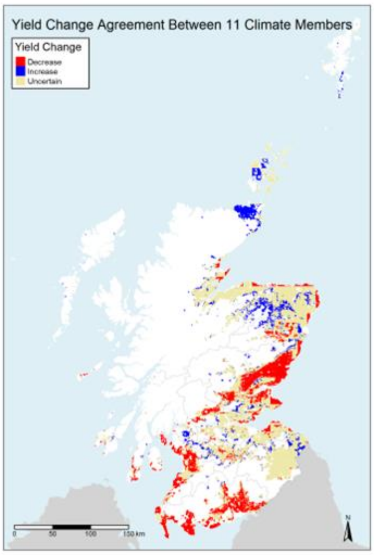
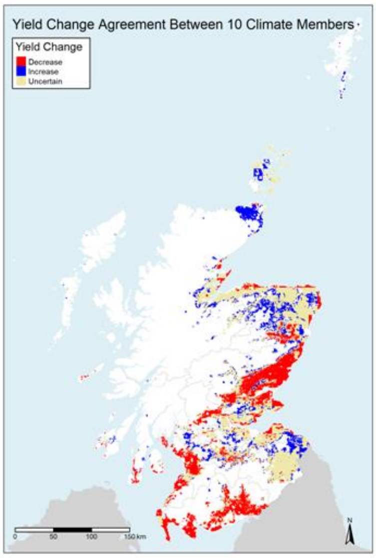
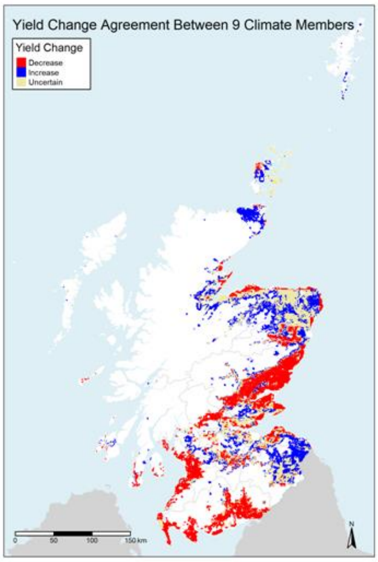
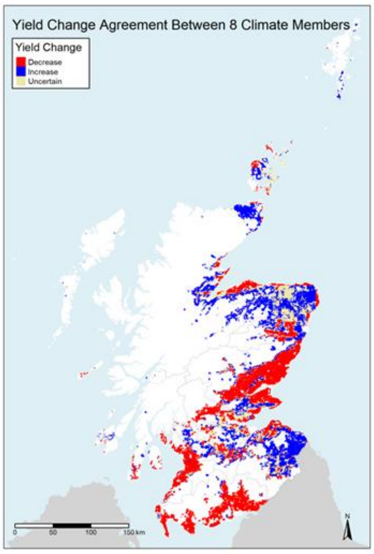
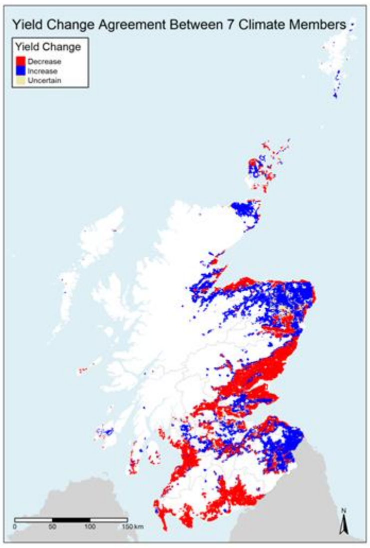
12 Ensemble Members	**11 Ensemble Members**	**10 Ensemble Members**
		
9 Ensemble Members	**8 Ensemble Members**	**7 Ensemble Members**
		

Figure 4. Spatial distribution of the level of agreement between climate projections (ensemble members) in the barley yield change over the period 2030-2049 as compared to the baseline period 1994-2015. Yellow = variable probability of change; Blue = yield increases; Red = yield decreases. The number of climate members considered for the agreement maps are, from top left to bottom right: 12, 11, 10, 9, 8 and 7. The maps are shown for the sowing date 01/Apr.

For these levels of agreement maps, where there is either increase or decrease, then we can be more confident with more that the projected yield change is likely to occur. Where there is no change, then we can be confident that there is less likely to be much change. The uncertain areas indicate a variable probability of change (could be either decrease or increase).

Land capability

A recent ClimateXChange Fellowship has implemented the Land Capability for Agriculture Classification System as a computing research platform (Udugbezi et al 2022). This enables future climate projections to be applied to the classification system to assess how climate change may impact land capability (see Figure 5 below).

Analysis between two baseline periods (1960-1990 and 1987-2017) indicated that climate change has already altered land capability and is likely to further impact it in both positive and negative ways in the future. These changes have been and will continue to be spatially and temporally variable.

There is a substantial risk that land currently classed as prime agricultural land (classes 1 – 3.1) may experience reduced production capability and flexibility due to dry soils in an increasing number of years with drought conditions. Conversely, potentially areas such as the north-west Highlands may experience increased precipitation totals in some years, meaning soils there becoming wetter.

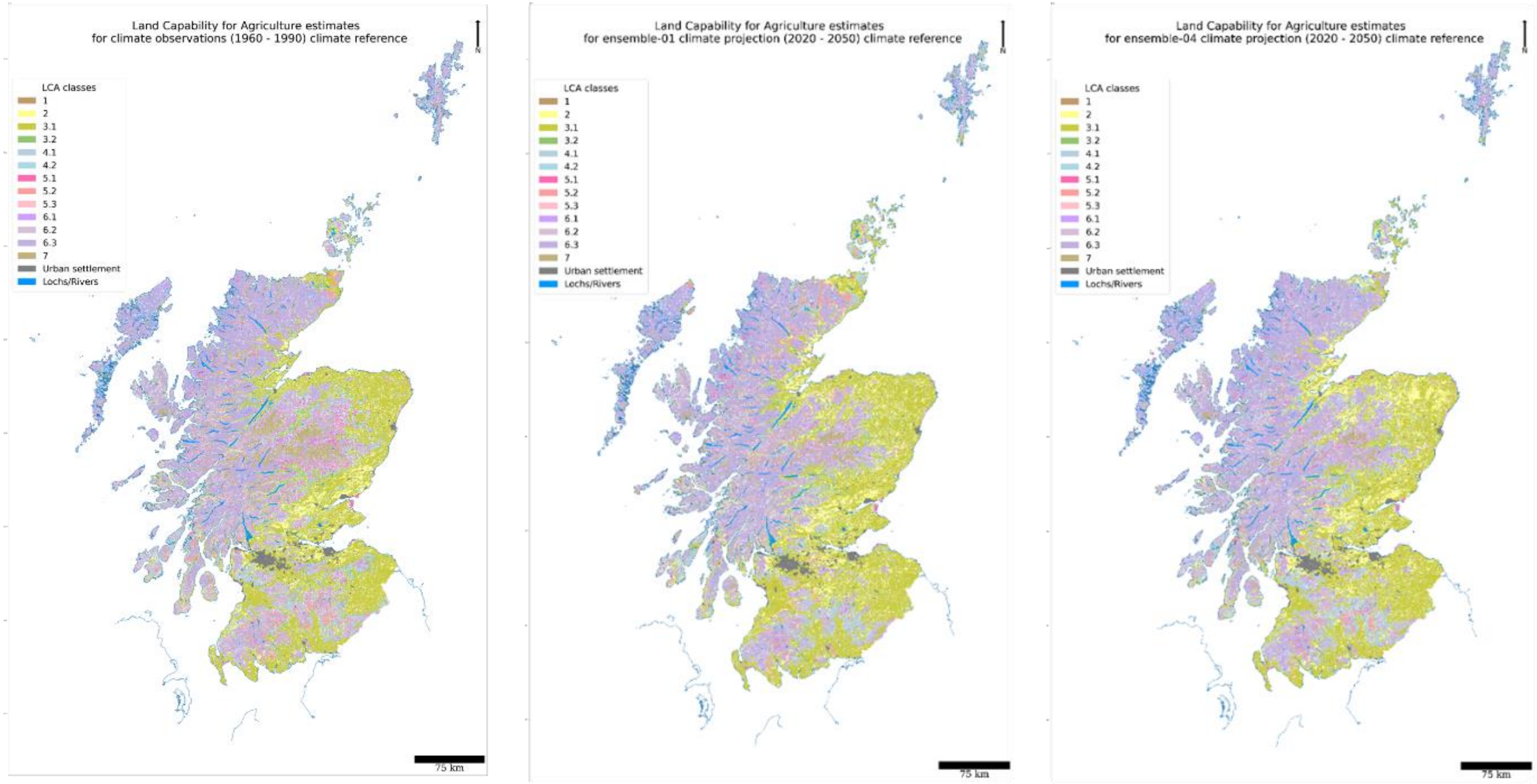
Two primary climatic factors are used in the LCA: Temperature – that is the amount of energy from the sun as input to land (represented by the accumulation of temperature); How dry a soil might become (the Potential Soil Moisture Deficit, PSMD). Assessments shows that both of these factors will be affected by climate change, meaning some soils are likely to become drier due to reduced rainfall and increased evapotranspiration (water returned to the atmosphere from plants and surfaces, e.g. soil), whilst others could potentially get wetter.

Reduced water availability is likely to be a key determining factor. Analysis suggests that soils, especially those with a low water holding capacity, are likely to become drier and with greater frequency. This means there is a risk of increased amounts of soil moisture deficit, meaning less water available for plants and more rain is needed to fill the soil profile up again.

This implies an increased risk of crops, grassland and vegetation experiencing difficulties in accessing water. The climate is projected to become more variable, hence a likelihood of fluctuations in a particular location experiencing dry and wet periods during the growing season.

Warmer temperatures will mean a more rapid accumulation of temperature. The rate of accumulation determines when plants and insects progress through their development stages (phenology), meaning crops may take less time to mature, but also not have as much time to accumulate biomass.

There is likely to be increased annual variability in land capability associated with increasing climatic variability and extreme events, such as wet seasons or years followed by dry ones.



Land Capability for Agriculture estimates for climate observations (1960 - 1990) climate reference

Land Capability for Agriculture estimates for ensemble-01 climate projection (2020 - 2050) climate reference

Land Capability for Agriculture estimates for ensemble-04 climate projection (2020 - 2050) climate reference

Figure 5. Estimated Land capability for Agriculture (new research platform version) for the baseline period (1960-1990)(left) and two climate projections: about 3% wetter and 2°C warmer (middle) and about 5% wetter and 2.3°C warmer (right) for the period 2020 – 2050.

Part 2: Overview of solution development issues

This part considers some of the broader issues concerning how solutions to the risks of climate change impacts on Natural Capital may be developed within the socio-economic and policy contexts.

Risks and threats

Abrupt changes in ecological systems are more likely to be influenced by climate extremes than by changes in mean climate (Turner et al., 2020); as extreme events are short-lived and difficult to predict, this means that climate-driven abrupt changes to natural capital are similarly likely to ‘come out of nowhere’ and are difficult to prepare against. Dependencies on Natural Capital in the forest industry generate most high financial risks (Smith et al., 2021), with nearly all these risks likely to be worsened by climate change. The forest industry may therefore be a prime candidate for gathering and presenting evidence of the consequences of weak climate policy.

Goyette & Smaoui (2022) showed that there is significantly higher likelihood of civil conflict under climate change in countries with low agricultural potential, relative to those with high agricultural potential. This finding did not depend on development levels, the contribution of agriculture to GDP or the presence of high value exports. It would be useful to know whether this finding was repeated for regional variations in agricultural potential within a country. This would highlight the variable capacity from local to national level government for handling food security-driven social unrest under a changing climate. It would also allow researchers to identify regional variation in the likelihood of civil unrest driven by climate and to highlight examples where this may already have happened (even at the level of political consequences for a failure to develop policies).

Spatial distribution of risks and opportunities

Declines in species richness are more likely in water-limited and/or colder temperature-limited climates (Harrison, 2020). For a country with wide geographical ranges in mean temperature and rainfall, this may allow us to identify areas more at risk of climate-driven species richness decline. While the discourse around NBS tends to assume that risk reduction is achieved locally, it ignores long-distance impacts (Solan et al., 2020). This may present an opportunity to explore how NBS can have an impact over longer distances (e.g., peatland restoration improving water supply for water companies, allowing them to reduce water treatment costs). Local and long-distance impacts of interventions therefore need to be considered.

Marais et al. (2020) explored the farm-scale value of agroforestry to Natural Capital and showed that the Natural Capital approach could be used to improve decision making in agroforestry at this scale for climate change mitigation. However, to do so would require improvements to the spatial resolution of Natural Capital assessment. Using a combination of remote sensing and ground-based measurements, Robinson et al. (2017) demonstrated that a natural capital accounting system could be developed that linked land use/cover information to soil carbon stock change accounting.

Morri & Santolini (2022) identified the need to demonstrate the role of natural capital in the production of public goods to rationalise payments for ecosystem services; they also highlighted the need for robust spatially explicit decision support tools incorporating cost-benefit analysis and modelling to support such payment mechanisms. Frameworks can be developed for assessing the vulnerability to specific types of climate-related events (e.g., Zhang & Liang (2021), who incorporated climate and non-climate indicators to develop spatial tools for determining adaptive capacity for winter storms in Iowa, or Aguilar et al. (2021) who associated natural, human, social, financial and physical capitals with resilience to water scarcity in Indonesia).

To be successful as well as useful, Natural Capital accounting therefore needs (and can potentially) be assessed at a resolution associated with landscape variability (i.e., less than 100 metres) while at the same time incorporating spatial and contextual interactions. Natural Capital accounting of linear features is intrinsically difficult. Significant uncertainty exists in the stock and rate of change of carbon in different ecosystems, as well as in the relative impacts of interventions that are known to reduce emissions/increase carbon storage, but whose impacts vary under different circumstances (European Environment Agency, 2022). Gomiero (2016) argues that because of large uncertainties of impact on soil natural capital and their associated risks, the precautionary principle should be used in assessing management scenarios.

However, it makes no sense to apply the precautionary principle to only some interventions. This highlights an earlier point made, that researchers need to be able to make recommendations based on imperfect information and often will not have much time in which to do so. To be able to perform with sufficient agility, we will need a safety net for the occasional times that we fail. As well as demonstrating that the consequences of doing nothing are worse than the consequences of making an occasional wrong recommendation, we need ways of making better recommendations with the information we have. To achieve this, we need knowledge frameworks.

Interactions between science and policy

To expand the discussion about climate impacts on Natural Capital and development of solutions, it is also useful to explore issues on the interaction between science and policy. Should dealing with climate change even be within the remit of policymakers? If the role of government is to provide services that individuals cannot effectively provide for themselves, then the answer is yes – as long as it is demonstrable that individual action alone cannot provide sufficient mitigation and adaptation. This is straightforward enough to do; if there are some people who are willing to damage the climate for their own gain (and there always will be) then government should have a role in regulating the activities of these people. The ‘public good’ nature of ecosystem services and Natural Capital mean that the state must play a major role in regulating, funding and facilitating payments to land managers for climate mitigation and adaptation interventions (Hodge, 2019). Where regulatory and market-based activities in response to climate change-based threats to natural capital are ineffective, policy options are needed to develop suitable interventions (e.g., Adamowicz & Olewiler, 2016).

Climate impact risk reduction is usually the poor cousin in families of policy priority; it is often hard to imagine a non-climate policy agenda being diverted or constrained by climate risk reduction priorities. Mehryar & Surminski (2021) compared 33 countries’ national laws relating to flood management in the context of climate change with case studies in disaster resilience from these countries. They found that while policies were shifting towards disaster risk management and climate adaptation, there was a lack of risk reduction strategies in policies or recognition of the impact of climate change on flood risk. They also found that natural capital was relatively unappreciated in its role in flood resilience, and that institutional ownership, responsibility and authority for reducing risk pre-flooding were lacking.

Keesstra et al. (2018) argues that several changes to how we think about and use the landscape are needed to achieve Land Degradation Neutrality (LDN). These changes include transformations in business models to accommodate environmental and social as well as economic valuation of land systems. They also argue that achieving these changes will require awareness raising of different governance options. Claret et al. (2018) demonstrated that Scotland has become 'an Ecosystem Services/Natural Capital literate polity' regarding the uptake of ecosystem services and natural capital within policy and land management decision making. An assessment of how this was achieved may provide insight useful for other countries aiming to achieve this goal; it may also provide ways for further improvement in this area in Scotland.

Seddon et al. (2020) highlights the urgent need for scientists, policymakers and stakeholders to engage with one another during the development of nature-based solutions, to avoid unintended consequences of poorly selected solutions that might result in ecosystem service trade-offs or socioeconomic damage. Lavorel et al. (2020) highlighted the importance of knowledge of co-production mechanisms to enable management and governance of ecosystem adaptation. It is therefore important that existing two-way mechanisms for communication between science and policy in Scotland (e.g., the Centres of Expertise) be exploited as much as possible. Researchers could possibly be more pro-active in finding ways to inform the commissioning process in the CoEs.

Several challenges can be identified in relation to Natural Capital and Ecosystem Service policy development. Bastien-Olvera & Moore (2020) recommend that the impacts of climate change on natural capital and the flows of ecosystem services should be better understood and incorporated into climate policy. A good example is where recent improvements in understanding of Natural Capital and Ecosystem Services benefits of river systems have led to improved river management techniques (Newson et al., 2021); however, further integration between policy, planning and implementation is needed to respond to climate change. An important part of this is the identification (and clear explanation) of uncertainties and quantification of risks. The focus in this paper is to identify various findings from the literature that provide opportunities for evidence-based policy development for Natural Capital and Ecosystem Services.

Long-term policies (i.e., longer than the usual democratic election cycle) are needed to drive investment in environmentally sustainable economic growth (Stern & Valero, 2021). Civil servants and scientists must therefore be involved as well as elected officials. Institutional ownership and authority to deal with climate issues before they emerge therefore needs to be improved, and science-policy dialogue needs to shift at least somewhat away from the 'they tell, we deliver' mentality. Given the image problem that science currently has in relation to informing evidence-based policy (Saltelli & Giampietro, 2017) on complex systems, this may seem difficult to achieve. Science (particularly environmental science) appears to have transitioned from the popular role of providing opportunities for better lifestyles to the unpopular one of telling people that there are limitations on resource consumption based economic growth. In later sections, opportunities to counter this framing are identified alongside the identification of risks and opportunities for Natural Capital under CC.

Cost-benefit and adaptive management

Innovation in Nature-Based Solutions (NBSs) presents an opportunity for developing cost-effective solutions for sustainability in Natural Capital (Faivre et al., 2017). However, NBSs have varying impacts across a range of landscape quality indicators (Sowinska-Swierkosz et al., 2021). A focus on Natural Capital can provide opportunities for green growth and sustainable development through the implementation of Nature Based Solutions (NBS). However, better understanding of the co-benefits and trade-offs of NBS within the environmental context of any situation is necessary to inform decision making (Martin et al., 2020). It is therefore important to achieve spatially explicit optimisation of NBS strategies to achieve specific desired outcomes in a place-based manner.

Cong et al. (2017) demonstrated that not only does managing soil Natural Capital well increase farm profit and reduce income risk but can also reduce the risk of negative consequences (downsides) of farm income risk. England et al. (2020) reviewed literature of the impact of woody systems (shelterbelts, riparian planting, silvopasture etc.) on Natural Capital assets in dairy systems. They found that both productivity and resilience were improved within systems where woody systems had been introduced, although evidence was sparse for some interventions. There is therefore definitely a strong economic case for, at least, some NBS.

However, moving too rapidly to argue purely based on economic benefits is problematic. Baciu et al. (2021) argued that an integrative assessment of the value of natural capital goods and services is needed rather than an individual valuation approach, because the ‘value’ of specific goods and services varies according to relevance, policy agenda and relevance to different stakeholders. Cost benefit analysis and valuation of natural capital and ecosystem services can change significantly over time due to social pressures. Hein et al. (2016) highlights this risk, arguing that management strategies that include multiple ecosystem services are more resilient against changing valuations.

Malhi et al. (2020) identified research and implementation priorities for maintaining natural capital under the threat of climate change. These include: the need for an adaptive management approach, highlighting that there are many ecosystem aspects that we will not understand in sufficient time to maintain in their current condition; long-term monitoring to allow detection of shifting baselines and to provide early warning of decline and tipping points; improved understanding of how to manage multiple ecosystem services simultaneously; linking empowerment in action to benefits from action. The impacts of land use and land use change on biodiversity need to be better integrated within modelling of land use change on landscape carbon storage (Molotoks et al., 2020); this highlights the risk and uncertainties around the possibility of negative consequences – we don’t want to solve climate change but kill off the biosphere.

Researchers working on issues of the climate and biodiversity crises therefore find themselves in an uncomfortable situation. Solutions are needed, and rapidly. However, there are substantial knowledge gaps (e.g., on ecosystem function responses to climate impacts) and researchers don’t have enough time or resources to gain a full understanding of the situation (e.g., ecosystem condition or health) or the effects (biophysical or economic) of possible interventions. What we do have is a good understanding what broadly will or won’t work in any given situation; we can also identify the interventions that we are not sure about. The challenge therefore is to find a way to recommend the interventions we are confident about to policymakers, while also dealing with the consequences of not always getting it exactly right. In other words, the research community need to be less risk-averse and at the same time, more resilient to the consequences of the occasional failure. One possible way to achieve both is to more effectively highlight and communicate the consequences of doing nothing.

Managing with imperfect knowledge

Brandon et al. (2021) argue that a more urgent need than standardised integration of all natural capital into economic accounting, is the requirement for frameworks that can incorporate Natural Capital into governmental decision-making regardless of whether or not the Natural Capital is formally accounted for. The term 'frameworks' can cover a broad church of concepts in this context, with many examples of previous work to select from. Farrell et al. (2021) highlighted several tools including the System of Environmental Economic Accounting Ecosystem Accounting (Ecosystem Accounting | System of Environmental Economic Accounting) (the acronym of which could rather misleadingly be pronounced 'easy') which was adopted by the UN Statistical Commission in 2021 and which has a robust structure and well-defined concepts. Farrell et al. also discussed the importance of non-monetary metrics of natural capital as a way of including multiple perspectives and qualitative Natural Capital indicators.

One of the ways in which researchers could improve the impact of using such knowledge frameworks is by not just using them as an internal research tool but implementing them in ways that are accessible and usable by other stakeholders. Access to low-cost tools providing freely available data is a barrier to community action. Ruckelshaus et al. (2020) highlight the benefits to disaster risk management from providing public and private sector organisations with data-rich tools for assessing and demonstrating the risk reduction benefits (and cost-effectiveness) of Natural Capital and nature-based solutions. This argument was also put forward by Watson et al. (2020) who additionally demonstrated the effectiveness of the EUNIS (European Nature Information System) habitat classification framework as an approach to quantify and value habitat ecosystem services.

Decision-making that will affect natural capital in agriculture, and associated risks and resilience, cannot be fully assessed without incorporating consideration of social capital as well (Kenny, 2017). The role of higher education and other social capital institutions in local climate change adaptation and natural capital management activities was found to increase the effectiveness of these activities in the north-east United States (Gruber et al., 2017). Researchers should perhaps therefore identify and use knowledge frameworks that can incorporate uncertain information and non-monetary accounting of Natural Capital, and that can also be used to express this information to non-scientific stakeholders to improve their capacity for taking action.

Attitudes, knowledge and behaviours

Scott et al. (2022) shows that the normalisation of acceptance of the environment's value and the need to protect natural capital is still at the stage of persuading relevant actors to accept this concept, and that it has not yet reached that stage of developing governance to maximise future impact ('mainstreaming'). While they argue that this is due to a lack of interdisciplinary and transdisciplinary approaches being adopted, it also seems that the costs and profits made from exploitation of/damage to natural capital are not borne by the same individuals. This reduces the incentive to act across all stakeholders, but there are likely other barriers to mitigation/adaptation activities among some groups.

Bruley et al. (2021) demonstrated through a workshop approach that ecosystem-based adaptation may not be constrained by natural capital but that a more likely barrier is a lack of collaboration and communication amongst stakeholders. In an analysis of barriers to adoption of measures to address flood vulnerability in the Netherlands, Oukes et al. (2022) found that physical, institutional and organisational barriers all existed in some forms. Inappropriate risk awareness and ambiguity regarding responsibilities were two of the institutional-organisational barriers alongside others. For ‘commons’ in Natural Capital, these two barriers to developing and adopting mitigation measures are considered likely to be frequently present.

Bottom-up citizen engagement approaches can improve risk awareness and local climate adaptation, although efforts are needed to improve appropriate citizen willingness to assume leadership positions and act autonomously (Thaler & Seebauer, 2019). In order to achieve this, it is first necessary to identify the capacity of individual citizens for assuming leadership roles. Natural Capital and learning/knowledge may be substituted for one another in successful adaptation to climate change within households and communities (Green et al., 2021), highlighting Natural Capital as a potential (but not absolute) indicator of adaptive capacity and the need to include other measures of community attribute within any framework for determining this capacity.

What this also tells us is that people with access to large amounts of natural capital may be best positioned to adopt significant roles in adaptation and therefore, potentially also mitigation. If large landowners also have less ambiguity about their responsibility in managing their capital (which seems likely) then they are doubly well positioned to lead adaptation/mitigation efforts. As we are seeing with the rise of Scotland’s ‘green lairds’, they are also well positioned to improve their income through payments for ecosystem services.

Improved investments in watershed-based climate change mitigation and adaptation will require lower institutional barriers to implementation and participation alongside market changes that account for natural capital (Vogl et al., 2017), and integrated catchment management (Stosch et al., 2017). Ardeleanu & Breaban (2021) demonstrated the importance of multi-institutional integration and coordination in the sustainable management of natural capital and correct implementation of payments for ecosystem services. One possible role that researchers could take to achieve a just transition for natural capital payments and avoid further inequality would be to employ the services of historians to identify and characterise to landowners the historical and likely future implications of unsustainable inequalities in ownership/control of natural capital.

Natural Capital accounting and payment for Ecosystem Services

Good protection and restoration of natural capital can contribute meaningfully to climate change mitigation. Where this protection causes a reduction in economic benefits usually gained from other, potentially more damaging uses of natural capital then fair compensation is a policy option. This promise of compensation will also act as an incentive to make changes. Barnes et al. (2021) made this point in relation to blue carbon in marine habitats, but the sentiment is true across all seminatural systems with high natural capital stocks. However, for this compensation and incentivisation to work, the payments made need to align with the benefits made from the ecosystem service gains. Accounting for the public good ecosystems services of agricultural land is vital to properly assess the market impact of land management decision making (Brady et al., 2019). Therefore, ecosystem services need to be accounted for.

A better way of assessing risks to natural capital is needed for decision-making in financial investment in agriculture; currently, decision-making is based on conventional financial and management indicators (Ascui et al., 2021). Improved risk assessment needs to take better account of land management impacts and dependencies on natural capital. Payment for ecosystem services can be linked to their capacity to mitigate risks from natural disasters, potentially pointing to a system of paying for natural capital as an insurance against risk (Valente et al., 2019).

A working framework for assessing Natural Capital within agricultural landscapes will need to incorporate inputs, outputs and flows from natural, social, financial and physical capitals (Aspinall & Staiano, 2019). Natural Capital and Ecosystem Services accounting is therefore not straightforward and requires sophisticated frameworks. Another of the challenges to valuing natural capital is that policy changes can cause rapid changes in perceived and monetary value (van der Ploeg & Rezai, 2020).

Flows between types of capital also need to be considered with Natural Capital and Ecosystem Services accounting. Acknowledging that net impact on natural capital can be wider than a single change and often involves impacts elsewhere, Houdet et al. (2020) demonstrated the use of double-entry bookkeeping approaches (i.e., where a movement out of one location can correspond to a movement into another, or to an impact on another natural capital stock elsewhere). The concept of inclusive wealth which combines capital across different types (e.g., Fenichel et al., 2016) is an important approach to evaluating changes and movements in wealth associated with natural capital under climate change. The main reason for this appears to be because inclusive wealth can accommodate changes in valuation of different types of capital and their transformation from one kind into another.

The IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) framework gives an example of integrating ecosystem services into natural capital assessment and accounting (Dimopoulos & Kokkoris, 2020). However, this framework does not appear capable of accommodating risk without further specification. Measures of inequity are often missing from corporate reporting of economic activities on natural capital (Lord & Ingram, 2021). Inequity of risk across demographics should be accounted for in any framework aligned with the Just Transition concept within climate adaptation and mitigation.

Because carbon emissions lead to long-term loss in natural capital, decreasing future output from Natural Capital, carbon taxes are seen as a way of future-proofing Natural Capital ‘income’. Barrage (2020) explored the impact of carbon levies on other tax income, in particular capital tax, and demonstrated that the welfare benefits of carbon taxation can be improved by considering this interaction. This highlights yet again the inherent difficulties of integrating Natural Capital into existing economic models and accounting frameworks. A root cause of these difficulties appears to be the legal distinction that exists between natural capital and other types of capital, in the sense that while Natural Capital can be legally owned it is not protected by property laws.

An assessment of existing Payment for Ecosystem Services (PES) schemes is necessary (e.g., Capodaglio & Callegari (2018) who highlighted that these schemes are often necessary in the absence of a comprehensive regulation framework and also pointed out that accounting for indirect costs is vital to the success of such schemes) to identify solutions appropriate to the Scottish context. Paid employment schemes to protect natural capital can be used to simultaneously target inequality, climate change impacts and biodiversity loss. However, for a scheme to be successful it must have a targeted design with clear and straightforward objectives (Norton et al., 2020).

The concept of fairness (e.g. Just Transition) must incorporate considerations of compensation and incentivisation in terms of who is entitled to be compensated (not only legally, but also in terms of basic needs) and who benefits from Natural Capital-based risk reduction interventions. The fact that Natural Capital can be transformed into other capital and in some cases vice-versa gives some people an opportunity to gain more capital at the expense of others (the Covid-19 pandemic has demonstrated this). A just assessment should consider not only how much some people have but how they obtained it. Sustainable distribution and consumption of natural capital requires a framework incorporating just needs, just entitlements and just deserts (e.g., Gabriel & Bond, 2019).

Evidence of no need for evidence

Cole et al. (2022) identified land management practices that mitigate the impacts of net zero practices on ecosystem services such as biodiversity and human wellbeing. They highlighted the importance of including social considerations of land management decision-making (to summarise imperfectly, reinforce peoples' connection with the landscape) in achieving successful transformations in landscape management and land use. This aligns with the author's personal observations that you can present as much scientific evidence as you like, but if local communities do not emotionally resonate with the need to change then nothing will happen.

Catalano et al. (2020) showed that while preventive intervention (before climate change impacts are felt) in small country economies leads to higher economic benefit than no action or remedial action, the high costs of early adaptation and budgetary constraints lead to a focus on late corrective actions. While these observations were focussed on financial capital, there is a similarity to be drawn with natural capital. Focussing the narratives around climate change to address the priorities of different political viewpoints may help resolve political deadlock over the responses necessary to climate change (Lucas, 2018).

The extent to which natural capital underpins and supports economic development is difficult to assess, but what can be shown is that in many cases, the potential for substituting Natural Capital with other forms of capital (i.e., manufactured or human) is low (Cohen et al., 2019) and can have consequences for sustainability (Islam et al., 2019). Attempts to place a purely economic valuation on Natural Capital are therefore missing the point that Natural Capital is not an interchangeable component of the economy. Clarke (2016) argues for natural capital to be recognised as underpinning or being critical for all other types of wealth generation.

It is possible that instead of looking for yet more evidence that natural capital should be protected to convince people with a conservative mindset, we should instead be making more of the threat to peoples' livelihoods from not acting. This does assume that researchers are willing to not only present arguments for change, but also to actually get their hands dirty occasionally.

The elephant in the room – regulatory weakness/capture

Accounting for climate change within financial systems remains challenging, with multiple approaches having been attempted across time and at different geographical scales (Bracking, 2019). The fact that none of these approaches has 'stuck' may demonstrate the lack of an effective accounting approach so far, or it could reflect a weakness in the fundamental assumption in economics that actors are rational. A third possibility is that this assumption of rationality is actually correct, but that economic theory fails to account for the distorting influence of legislative and media capture by emitting industries. If this possibility is correct, then any accounting framework seeking to incentivise preservation of future Natural Capital income will need to link payments today with continuing wealth tomorrow.

Shared socioeconomic pathways (SSPs) that have high investment in a range of societal areas demonstrate relatively high levels of inclusive wealth and reduced use/damage of natural capital, while those SSPs with lower societal investment Kurniawan & Managi (2018) have greater inequality and risk for Natural Capital. Drives to reduce societal investment by some sections of society can therefore be interpreted as a drive towards avoiding inclusive wealth and cementing power over others in the hands of those who already have it; a key objective for those aiming to increase societal wealth and inclusivity must therefore be to counter this drive to reduce societal investment, however it is formulated.

Olivier (2018) highlights existing evidence that one of the major (possibly the most significant) barriers to achieving natural capital sustainability is the range of activities adopted by neoliberal capitalist organisations. Market-driven nature-based solutions for carbon storage can result in negative social impacts and can also produce false claims of positive environmental impact (Richards & Lyons, 2016). In addition to this greenwashing, active disinformation hampers public acceptance of scientific evidence of the need for action (Lewandowsky, 2021).

Researchers tend to avoid formally using this evidence to avoid being labelled politically biased, while openly acknowledging amongst themselves that without addressing this issue, meaningful change will not be achieved. While even the UN Secretary General acknowledges that fossil fuel companies are actively working against evidence-based climate policy (Fossil fuel firms ‘have humanity by the throat’, says UN head in blistering attack | Climate crisis | The Guardian), a challenge exists as to how the neoliberal capitalist stance can be tackled while maintaining scientific objectivity and research funding.

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