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Climate Change, Natural Capital and Adaptation in Scotland's Marginal Lands

Robin J Pakeman, Alessandro Gimona, Miriam Glendell,Jagadeesh Yeluripati, Steve Addy, Freddy van Hulst, Keith Matthews, Ruth Mitchell and Mike Rivington, The James Hutton Institute; March, 2018

Executive Summary

The boundary between productive land and hill land in Scotland has moved over time, in response to climate and also to market demand. Scotland's climate is changing, and this will mean changes for those areas of Scotland that sit on the margins of productive agriculture.

Over large areas, including many areas of marginal land, climate change will likely benefit agricultural production, though in drier areas productivity might be constrained by drought. Climate is not the only constraint; some sites are steeply sloping or have soils that are difficult to work, and these sites may see limited changes. In other areas increased climate variability may make it risky to change land management.

The Adaptation Sub-Committee, in its UK Climate Change Risk Assessment 2017, identified sustainable soil management as a specific challenge as Scotland adapts to a changing climate. The potential impact of climate change on marginal land was identified by ClimateXChange researchers as being particularly important because of the level of ecosystem services currently provided by these areas. We illustrate this potential by examining the four dominant ways that farmers will adapt to climate change, and their impact on different services.

Key findings

- It is likely that land use change will result in the intensification of land management. The result would be a reduction in most aspects of natural capital including soil carbon, water quality and biodiversity. An increase in arable cropping from current levels and a switch to winter cereals could increase soil erosion and flood risk.
- An exception would be the potential increase in forestry and woodland, though the benefits of planting depend greatly on what is planted and where it sits within the landscape or catchment.
- It is particularly difficult to assess the likely changes in livestock numbers. This makes it difficult to assess the greenhouse gas emissions from their rearing, as it is not possible to predict the balance of their removal to allow arable cropping, the increase in extensive livestock management which would affect emissions intensity, and the intensification of management on currently more marginal ground.
- One approach to assessing the risk of autonomous adaptation would be to model the impacts of a set of scenarios of change so that comparison could be made with changes expected from other drivers; if potential impacts are large in comparison then greater attention would need to be given to strategies to avoid or mitigate impacts.

A synthesis of the findings for the individual land use conversions are shown in Table 1.

Table 1. A summary of the main impacts of the different land use conversions considered; ↑↓ net positive benefits of the conversion, ↑↓ net negative impacts of conversion, ↔↕ equivocal or context dependent impacts.

	Conversion of improved grassland to arable	Improvement of grassland	(Re-)conversion of rough grazing to permanent pasture	Conversion to forestry or woodland
Soil carbon	↓	↑	↑	↑
GHG emissions	↕	↑	↔	↓
Water quality	↓	↓	↓	↕
Pathogens	↓	↑	↑	↓
Flood risk	↑	↑	↔	↓
Biodiversity	↕	↓	↓	↕
Future robustness	↓	↔	↔	↔

Content

Introduction

What is marginal land? What is marginal land being used for now?

In Scotland the Land Capability Classification (Appendix 1) has been developed to grade agricultural land on a scale from 1 to 7. Prime land, classes 1 to 3.1, is suitable for growing a wide range of crops and accounts for around 8 % of what might be termed rural land (Table A1). For the purposes of this report marginal land is defined as the range from where arable cropping is possible but there are restrictions on crop choice and risks are higher (class 3.2) through to the best quality rough grazing (class 6.1).

A summary of predicted climate change

The UK Climate Projections 2009 (UKCP09) indicate that Scotland's climate will become warmer throughout the year. The projections also indicate that rainfall is likely to become even more seasonal, with an average summer becoming drier, while autumn and winter become wetter. There will also be an increase in variability in rainfall with more frequent summer droughts and more episodes of high rainfall, particularly in the winter. Revised projections are expected later in 2018 (UKCP18). It is likely that these changes will have a significant impact on the capability classifications of the land.

New land use options for marginal land as climate changes

Farmers and land managers have always adapted to their conditions, whether that be the availability of capital to invest, market demand for produce, and profitability, as well as natural constraints on land use such as slope and soil conditions (Brown & Castellazzi 2014). Decisions will also be affected by potential changes in climate variability which might make changing land use risky. Some farms in marginal areas already have a mixed farming approach (17.6 % of the area of 3.2, 10.1 % of 4.1 and 7.7 % of 4.2, Figure 1) so the potential to shift the balance in these farms towards arable is easier than if a new form of management had to be adopted from scratch. Grass-based farming operations will have machinery available to increase management intensity, so in these farms the operational capacity to adapt is already present. Ultimately, changes will be driven by interactions between climate change, market demands for produce and the support mechanisms available to land managers.

We have examined the four likely dominant adaptation options. We restrict our analysis to these four as shifts such as rough grazing to arable are unlikely to be frequent:

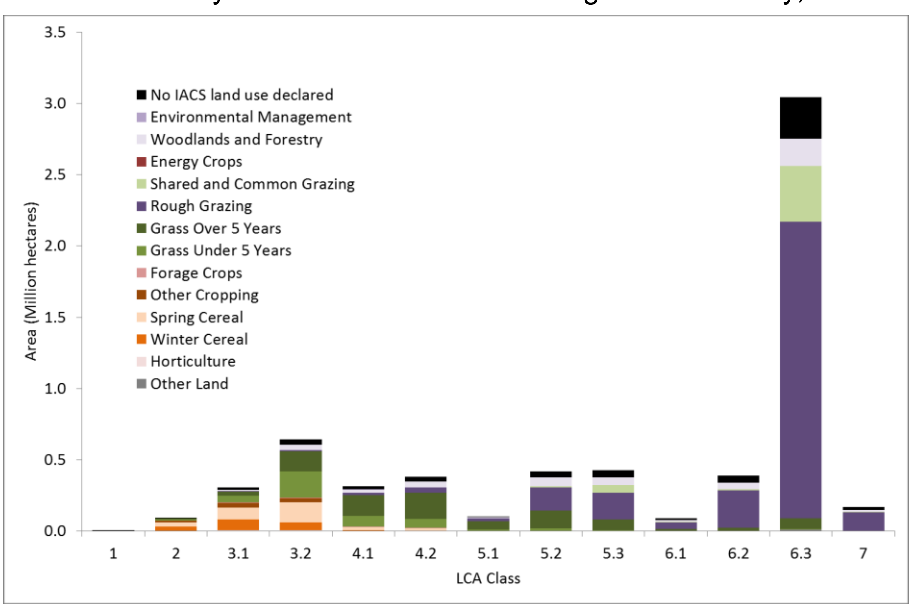

Figure 1 IACS land uses (2011) broken down by LCA class

1. **Conversion of improved pasture to arable:** This could take the form of increased years under arable in an arable-grass rotation, or the ploughing of land that had been under grass for considerable time.
2. **Intensification of management of permanent pasture:** This could take the form of more frequent re-sowing of agricultural varieties of grass and clover or increased fertiliser use to take advantage of potentially better growing conditions, though increased climate variability may limit vehicle access under wetter conditions. It could also allow additional silage cuts which would increase fertiliser requirements and potentially increase nutrient runoff.
3. **Conversion of rough grazing to permanent pasture:** This may represent reconversion of land initially improved in the 1960s and 70s, when grants were available for drainage, fertilisers and liming, that has been recolonised by native species, or improvement of land previously not improved. It should be noted that all land up to class 5.3 could be converted to improved grassland.
4. **Increase in forestry and other woodland cover:** Scottish Government policy is geared towards increasing tree cover (from 17 to 25 % of land area) but improved growing conditions may make a switch to forestry more likely in the more marginal ground. This is an option for all classes except for 7 and some of 6.3 (Bibby et al. 1988) but is less likely on land capable of good agricultural returns.

The impacts of these changes at the field scale will be considered and the wider implications of combining these local changes at catchment and national levels discussed later. The impacts are grouped together under four headings: soil carbon and greenhouse gas emissions; freshwaters; biodiversity; robustness of land use system in light of future climate driven impacts.

Consequences of conversion of improved grassland to arable

Arable based agriculture generally offers the best returns and increasing demand for grain products will likely continue. This could lead to the conversion of grassland to arable on the best marginal land as average temperatures improve, though this is unlikely to be significant where dairy farming is dominant. Decreasing production from prime land as a result of drought limitation might help fuel this change.

In addition to a change in land use, there may also be an intensification of arable production. This may result in increased use of pesticides and fertilisers as well as impacts on biodiversity, as well as a shift from spring to winter cereals. This latter change allows soil to be exposed to erosion risk for longer (Davidson & Harrison 1995).

Soil carbon and greenhouse gases

Several studies have demonstrated that grasslands in Scotland are net sinks for soil carbon (Salisbury et al., 2016). Existing evidence suggests that soil carbon is lost if improved grassland is converted to arable land (Spohn & Giani 2011). Arable crops are harvested annually and most of the harvested above ground biomass is removed for other uses, whereas in grassland there is the potential for long-term storage potential in soils. It is difficult to assess the average rate of loss of soil carbon from improved grassland to arable transition as there is very little data available in a Scottish context, but average carbon contents for arable soils are roughly half of those for improved grassland (12.3 g kg^{-1} v. 23.6 g kg^{-1}, respectively, Chapman et al. 2013). The balance between arable and grassland in terms of their greenhouse gas (GHG) emissions depends upon methane production from livestock, fertiliser and lime use, manure management, tillage practices and fuel use by agricultural machinery. Greenhouse gas emissions from agriculture are largely associated with nitrous oxide emissions.

Nitrous oxide emissions from Scottish Agriculture in 2014 were estimated to be 2.7 Mt CO2e. Calculations at the field scale suggest the conversion from beef or sheep production to arable would increase GHG emissions, whilst conversion from dairy to arable would decrease emissions (Fielding & Matthews 2014). However, it should be stressed that assessing impacts is challenging due to limited data, a lack of research applicable to Scottish soils and limited ability to address interaction effects.

Freshwaters

Understanding the likely impacts of future land use and climate change on water quality (Gilvear et al., 2002) and quantity (Dunn and Mackay, 1995) is challenging. Studies addressing this question at a scale useful for decision makers are scarce (Dunn et al., 2015; Sample et al., 2016; Watts et al., 2015) and our confidence in predicted impacts on water quality or river ecology is low (Watts et al., 2015), though in general water quality is poorer in areas dominated by intensive agriculture (Towers et al. 2017). Changing climate, especially changes in seasonal precipitation and mean annual runoff, as well as projected increase in rainfall driven erosion as rainfall intensity increases (Panagos et al., 2017; Poggio et al., 2018) could lead to increased transfer of pollutants and sediment. The overall effects of marginal land conversion on water quality in Scotland are likely to be demonstrated at river reach and catchment scales, particularly in downstream locations, where nutrients can accumulate in standing waters (Stamm et al., 2014). Arable land use is associated with additions of both organic and inorganic fertilisers and other agrochemicals, resulting in a risk of export of dissolved and particulate nitrogen and phosphorus, organic contaminants (pesticides, herbicides) and sediments (Dunn et al., 2015). Therefore, conversion to arable land is likely to have a negative effect on the concentrations and loads of these contaminants in rivers and lakes. Conversely, pasture land is associated with a higher risk of pathogen contamination (faecal indicator organisms or FIOs), therefore conversion of pasture to arable may reduce the risk of microbial contamination of freshwaters (Bussi et al., 2017; Dunn et al., 2015), although pathogens associated with particulate sediment may increase (CREW 2012). Intense agriculture land use practices depending on the catchment specific influences on hydrology (Capell et al., 2013), could potentially increase runoff responses causing increased flood risk downstream (O'Connell et al., 2007).

Biodiversity

As a result of their intensive management both arable and improved grassland are relatively restricted in terms of their species richness for plants, so a conversion would just see a shift in the identity of the "weed" species. Similar arguments could be made for other groups such as plant feeding insects, so those associated with grassland plants would be replaced by those associated with arable plants, but higher insecticide use would reduce the overall biomass of invertebrates available for insectivorous birds. Increasing the area of arable farming could benefit a range of seed-eating birds, such as corn bunting and yellowhammer, but it could reduce the abundance of birds associated with grasslands such as geese and starlings (Robinson et al. 2001). However, it could be argued that a complete shift to arable might allow a greater choice in agri-environment options (as options can be followed that are compromised by grazing animals) that could be used to improve habitat for key pollinators such as bumble bees and butterflies (in line with the Pollinator Strategy for Scotland), and, especially, seed-eating farmland birds such as corn bunting in order to address the commitments in the Scottish Biodiversity Strategy and the Aichi targets. There would also be a shift in the soil microbial community and a loss of diversity (Tsiafouli et al. 2015).

Robustness of new land use

Without a permanent vegetation cover there are periods when arable soils are vulnerable to erosion when heavy rain coincides with bare soil (Davidson & Harrison 1995), which is especially true for winter cereals. The projected increased incidence of high rainfall events (Committee on Climate Change, 2017) will mean that increased arable production or a switch from spring to winter cereals, particularly on the steeper ground found in marginal lands, could lead to more frequent events of rapid runoff leading to flooding and enhanced nutrient and sediment run-off with potential negative consequences for the ecological status of waterbodies. Also, the increased incidence of summer drought could reduce production from arable crops (Committee on Climate Change, 2017) or shift production to drought tolerant crops such as maize (which is high risk for erosion).

Consequences of improvement of grassland

Soil carbon and greenhouse gases

Improving grassland requires an intensification of management activities, including ploughing and drainage, leading to higher levels of soil disturbance and hence higher levels of carbon oxidation and loss (Hopkins & Lobley, 2009). A literature review conducted by Moxley et al. (2014) concluded that grassland improvement could increase soil carbon stocks under pasture on mineral soils. However, the review also concluded that intensifying management of rough grazing on organo-mineral soils (the dominant soils under marginal land) could result in a loss of soil carbon; though they also pointed out the lack of field data to quantify the effect of intensifying grassland management on soil carbon stocks and greenhouse gas emissions. Overall uncertainty regarding the impact of grassland management on soil carbon is high, but a recent synthesis by Conant et al. (2017) assembled data from hundreds of studies concluded that improved grazing management, fertilisation, sowing legumes and improved grass species and irrigation all tend to lead to increased soil C, at rates ranging from 0.105 to more than 1 Mg C ha^{-1} yr^{-1}. The management practices intending to increase forage production tend to increase soil SOC stocks (Conant et al., 2017). Practices that change system nitrogen dynamics, such as fertiliser application, are likely to change N2O fluxes.

Freshwaters

Intensification of grassland management will likely lead to reduction in water quality (Dawson and Smith, 2010), particularly in terms of suspended solids and dissolved and particulate phosphorus ((Bilotta et al., 2010, 2008), microbial water pollution (Dunn et al., 2015; Tetzlaff et al., 2012) but also ammonia, nitrate, dissolved organic nitrogen, particulate organic carbon and nitrogen and organic contaminants (Dawson and Smith, 2010), with likely consequences for the water quality status of standing waters and certain river reaches. Conversion to improved grassland could also potentially have implications for catchment hydrology leading to increased catchment runoff and heightened flood risk downstream (Orr and Carling, 2006; O' Connell et al., 2007). Furthermore, where areas converted to improved grassland coincide with floodplains, the resulting simplification of vegetation could reduce surface hydraulic roughness (Chow, 1959) resulting in quicker movement of out of bank river flows that cause increased flood risk downstream.

Biodiversity

There is a clear relationship between grassland plant diversity and nitrogen fertiliser use; as fertiliser use increases diversity drops and the largest drop is over the range 0 to 100 kg N ha^{-1} yr^{-1}, with fewer losses above 100 (Tallowin et al. 2005). Invertebrate diversity will parallel this drop in plant diversity, and has negative implications for habitat use by bats (Walsh & Harris 1996). Intensification also reduces the suitability of grasslands as feeding (drop in invertebrate abundance, seed abundance) and breeding (increased vegetation height, disturbance by livestock and mowing) habitat for many bird species (McCracken & Tallowin 2004; Vickery et al. 2001). There would also be significant shifts in the below-ground biodiversity, with a shift to bacterial instead of fungal dominance, and a general reduction in diversity (Bardgett & Cook 1998).

There is potential for improving the biodiversity of improved grasslands but as intensive use is inimical to most species, benefits will largely come from enhanced management of field boundaries, such as hedgerow planting.

Robustness of new land use

As the main vegetation cover has not changed then there is little impact on the risks of erosion, except during reseeding. Warmer temperatures will benefit grassland productivity and extend the growing season, though the opportunity to increase the period of outdoor grazing may be reduced by poaching resulting from increased precipitation (Climate Change Committee 2017). Grassland productivity is most likely to decline in drier areas in the east and there is evidence that the reduction in diversity of the vegetation that accompanies intensification will exacerbate this (Pakeman 2014).

Consequences of (re-)conversion of rough grazing to permanent pasture

There may be little conversion of rough grazing to permanent pasture as uncultivated and semi-natural areas are protected from conversion to intensive agricultural purposes under the Environmental Impact Assessment (Agriculture) (Scotland) Regulations 2006. However, this does not prevent small projects (< 200 ha) being converted and it could be argued that the regulations do not prevent the re-conversion of previously improved grasslands that have partially reverted. However, as a result of farming's retreat from the hills and decoupling of payments there may be little capacity for change in these more marginal areas.

Soil carbon and greenhouse gases

Conversion of rough grazing to permanent pasture involves intensification of grassland management which includes an increase in nutrient fertilisation, greater livestock density and, where there is silage production, a higher mowing frequency. An increase in N2O emissions will follow the application of synthetic fertiliser, but soil carbon sequestration would be enhanced by both organic and inorganic fertiliser could significantly influence soil C sequestration. Permanent grasslands are likely to mown frequently and most of the above ground productivity is removed and so not contribute to C inputs to soil. Management practices intending to increase forage production tend to lead to an increase in soil C (Conant et al. 2017). Histov et al. (2013) pointed out that improving forage quality and the overall efficiency of dietary nutrient use is an effective way of decreasing GHG emissions per unit of animal product. The overall changes to soil carbon sequestration and GHG emissions due to the conversion of rough grazing to permanent pasture depend on the shift in management intensity.

Freshwaters

As for the previous section, intensification of grassland management would likely lead to reduced water quality through increased suspended solids (carrying carbon, nitrogen and phosphorus), dissolved ammonia, nitrate, organic nitrogen and phosphorus, as well as microbial water pollution and organic contaminants (Bilotta et al., 2010, 2008; Dawson & Smith, 2010; Dunn et al., 2015; Tetzlaff et al., 2012). Conversion of marginal land to permanent pasture would be expected to lead to similar increased water runoff sensitivity as other grass or crop land conversions (Orr and Carling, 2006; O'Connell et al., 2007).

Biodiversity

The same issues relate to the (re-)conversion of rough grazing into improved pasture as for the intensification of management of existing pasture, except that the losses of diversity will be more substantial as the change in diversity is most rapid a low levels of nitrogen fertiliser use (Tallowin et al. 2005). The conversion could see habitats listed in the Scottish Biodiversity List impacted including upland hay meadows, calcareous grassland and heathland. It would also impact the animal communities of such habitats, including birds such as curlew, lapwing, ring ouzel and many butterfly and moth species. The associated decline in insect pollinated herbs (Pakeman et al. 2017) would also impact on agriculture as there would be a reduction in pollinator availability for key agricultural and horticultural crops in surrounding areas (Öckinger & Smith 2007). It may also impact a number of predators which rely on the small mammals and birds associated with rough grazing (French & Picozzi 2002).

Robustness of new land use

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Consequences of conversion of marginal agricultural land to forestry or woodland

It is unlikely that large areas of the best marginal land will be planted and hence most new forestry and woodland will be planted on the less productive ground where improved timber yields may make forestry more attractive. However, agro-forestry, shelter belts and riparian planting may be taken up on the better ground for other benefits.

Soil carbon and greenhouse gases

It is estimated that around 10 million tons of CO2 (net) is accumulated annually by forests in Scotland (Forestry Commission 2009). Expansion of forest, especially on marginal agricultural land on mineral soils (the best marginal land), leads to greater carbon sequestration. Towers et al. (2006) pointed out that planting trees on low carbon soils would offer the best mitigation potential. There is general consensus and evidence that conversion of marginal land on mineral soils to woodland will have positive impact on soil carbon and GHG emissions, though planting decision need to take into account conflicts with other goals such as the Scottish Biodiversity Strategy and the need to conserve peat soils which become net carbon sources when drained and planted for forestry (Simola et al. 2012).

Freshwaters

The effects of woodland management on water quality are highly dependent on species, site and soil type, and silvicultural practice (Dunn et al., 2015). Conifer afforestation may reduce the summer minimum low flows potentially impacting on the dilution ability of headwater streams, however, native woodland is expected to have less adverse effects (Gilvear et al., 2002). Furthermore, native riparian (riverside) woodland may help to mitigate increases in water temperatures (Hrachowitz et al., 2010), especially as streams most at risk of increasing temperatures are small upland streams at exposed locations without any forest cover and relatively far inland (Hrachowitz et al., 2010) – which could include many in marginal land areas. Conversion of pasture to forest land may lead to reduction in microbial contamination, specifically of faecal indicator organisms (FIOs) from livestock (Bussi et al., 2017; Tetzlaff et al., 2012).

Intermittent fertiliser additions and increased capture of atmospheric pollutants (N and sulphur) through forest canopies, particularly in areas of high N deposition, increase soil N saturation, leading to higher losses of diffuse forms of N with increasing mean annual temperature, (Dawson and Smith, 2010; Dise et al., 2009). Conifer afforestation is also associated with enhanced manganese (Mn) in runoff, which can be toxic to fish and impair drinking water quality, particularly in upland areas (Heal, 2001). Locating conifer plantations away from riparian zones and hydrologically connected areas reduces the risk of increased Mn concentrations in streams (Heal, 2001) as well as nitrate and sediment pollution after clear-felling. Conifers and short rotation coppice should be avoided in acidic catchments, especially where freshwater are already acidified. Sympathetic management practices such as continuous cover forestry, rotational felling and management of the riparian zone would also reduce the impact of woodland plantations on freshwaters (Burgess-Gamble et al., 2017; Neal et al., 2004).

In terms of flood risk, afforestation may lead to higher evapotranspiration rates from forest cover at catchment scales (Capell et al., 2013), thus potentially reducing summer river flows in susceptible catchments (Iacob et al., 2017; Soulsby et al., 2017), although current evidence for climate change driven summer flow reductions in Scottish catchments is low (Hannaford and Buys, 2012). At the local scale Thomas and Nisbet (2007) suggested that strategically planted woodland in floodplain areas could help to increase temporary water storage and delay the movement of floods downstream. However, a recent empirical study suggests that while afforestation may help to mitigate against flood risk from some smaller and moderate summer floods, it is unlikely to reduce the risk posed by the largest and most economically damaging floods (Soulsby et al., 2017). Demonstrating the effect of afforestation on peak flows is difficult, especially for larger events and where the extent of afforestation is <15-20% of a catchment (Burgess-Gamble et al., 2017; Iacob et al., 2017), therefore, unless very extensive, afforestation (especially that involving native tree species) is unlikely to have a significant effect on flood risk reduction on marginal land.

Biodiversity

The conversion of open land to forestry or woodland means a considerable shift in species composition of all groups. In general the shift to coniferous plantations is thought to be locally detrimental to biodiversity if the shift is from semi-natural habitats, but relatively neutral if the shift is from intensively farmed habitats (Bremer & Farley 2010). If large blocks are converted to broad-leaved woodland their value will increase as they age (Bowen et al. 2009). The conversion to broadleaved woodland, if appropriately located, would be beneficial for woodland species such as spotted flycatcher and many warbler species. New woodland patches can enhance the connectivity of semi-natural woodland habitat (presently very fragmented and under-represented in Scotland) over wide areas, facilitating the range shift of some species that will need to adjust their distribution due to new climatic conditions (Gimona et al., 2012; 2015).

There are well known negative impacts of increased woodland cover on species such as curlew in surrounding habitats, as a result of increased cover for predators (Douglas et al. 2014), as well as for dunlin and golden plover (Wilson et al. 2014). So increased forestry and woodland cover can have impacts beyond the land planted.

Robustness of new land use

As for arable land, there is the potential for enhanced soil erosion if high rainfall events occur post-harvest. Forest productivity will be enhanced in western and northern areas where the balance between increased growth from higher temperatures and restriction by summer drought are positive (Committee for Climate Change 2017); eastern and southern areas may see some reduced productivity as a result of drought limitation.

Discussion

The sections above highlight the potential impacts of the main, likely adaptation by farmers that could take place driven by climate change. For these transitions we have a reasonable certainty about their impact, or at least the direction of impact, on natural capital at the field scale. For example, we know that ploughing will release carbon from the soil and increase the risk of soil erosion, intensifying the use of grasslands will reduce their value for biodiversity and increased fertiliser use will result in reduced water quality. Most of the considered changes represent intensification of agriculture and this process goes against trend of trying to support natural capital in the face of increased agricultural pressure.

However, there are three major sources of uncertainty in predicting impacts.

Firstly, the degree and rate of adaptation is difficult to assess given that it depends on many simultaneously operating drivers; climate averages and variation, capacity to adapt, wider economic circumstances like commodity prices and future government support for agriculture and natural capital.

Secondly, given the uncertainty in the degree of adaptation in terms of the transitions, it is difficult to scale-up changes at the local level. For instance, reduction in livestock numbers on the best marginal land may be higher, similar or smaller than increases on more marginal land. Without that certainty, the overall changes in greenhouse gas emissions from livestock is impossible to predict. This is important given that methane emission from livestock account for around a half of total agricultural greenhouse gas emissions.

Thirdly, a number of effects do not scale linearly from field scale changes in land use. For instance, the response of curlews to woodland in the landscape operates at a scale of up to a kilometre through increasing cover for predators (Douglas et al. 2014), hence integrating the impacts of planting new woodland within the landscape is difficult to predict. Overall, the balance for biodiversity is likely to depend on whether the land use transitions increase or reduce heterogeneity in the landscape (Benton et al. 2003). Similarly, the impacts of any land use change in marginal areas on hydrology will depend on the scale of changes relative to catchment size and the specific characteristics of the catchment. The catchment specific nature of topography, soil, drainage networks and existing land use could all affect hydrological responses under climate change (Capell et al., 2013). Superimposed changes to land use depending on their nature could also in turn have implications for runoff. Generally speaking, conversion towards more intense grazing and arable land uses, results in increased runoff response at small catchment scales but empirical evidence of these effects at larger catchment scales is lacking (Orr and Carling, 2006; O'Connell et al., 2007).

This document was put together to initiate debate. It highlights that predicting the impacts of autonomous change would be challenging. One potential approach would be to model the impacts of a set of scenarios of change on specific aspects of natural capital so that comparison could be made with how those specific aspects of natural capital are affected by other drivers. For instance, the scale of climate driven change in soil carbon across Scotland could be compared with that released/captured as a result of different scenarios of land use change in marginal lands. This is easier for some aspects of natural capital such as soil carbon and livestock methane emissions. It would be harder to assess these scenarios for even a small number of measures of biodiversity where evidence is poorer.

Many of the changes as a result of autonomous adaptation could have a negative impact on natural capital. Consequently, consideration should be given to ways of mitigating these impacts as they occur, rather than waiting until impacts become serious. For example, this could be achieved by incorporating woodland planting into areas seeing intensification in order to mitigate soil carbon losses and reduce flood risk, or actions to improve biodiversity through habitat restoration or creation.

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Appendix 1 - the Land Capability Classification

Land capability classification systems are based on defined biophysical limitations on land use, including climate, soils and topography. They can therefore communicate complex information in an accessible format for both scientists and decision-makers (e.g. Brown et al., 2011). When such information is mapped it can contribute to decision making on spatial planning and to policy aimed at adaptation and mitigation of climate change.

The Land Capability for Agriculture classification system in Scotland (Bibby et al. 1982; Brown et al., 2011, see Table 1) is widely accepted and used by planners and land managers, with the best quality ('prime') land retaining a degree of protection in the planning system. It classifies land based on its climate, slope, soil type and wetness, erosion risk and vegetation present.

Table A1. LCA classes and associated land uses (Bibby et al. 1982). Areas taken from the 1:250,000 scale LCA – with a consistent basis across Scotland. Lower classes tend to be under represented in this dataset.

Class	Category	Climate limitations	Land use	Area ('000 ha)	% of LCA classes
1	Prime	None or very minor	Very wide range of crops with consistently high yields	4	0.1%
2	Prime	Minor	Wide range of crops, except those harvested in winter	175	2.3%
3.1	Prime	Moderate	Moderate range of crops, with good yields for some (cereals and grass) and moderate yields for others (potatoes, field beans, other vegetables)	447	5.9%
3.2	Non-prime	Moderate	Moderate range of crops, with average production, but potentially high yields of barley, oats and grass	701	9.2%
4.1	Non-prime	Moderately severe	Narrow range of crops, especially grass due to high yields but harvesting may be difficult	371	4.9%
4.2	Non-prime	Moderately severe	Narrow range of crops, especially grass due to high yields but harvesting difficulties may be severe	469	6.2%
5	Non-prime	Severe	Improved grassland with mechanical intervention possible to allow seeding, rotovation or ploughing. Three divisions (5.1, 5.2, 5.3) based on increasing difficulty of improvement.	1,406	18.5%
6	Non-prime	Very severe	Rough grazing pasture only. Three divisions (6.1, 6.2, 6.3) based on decreasing grazing value.	3,779	49.7%
7	Non-prime	Extremely severe	Very limited agricultural value	257	3.4%

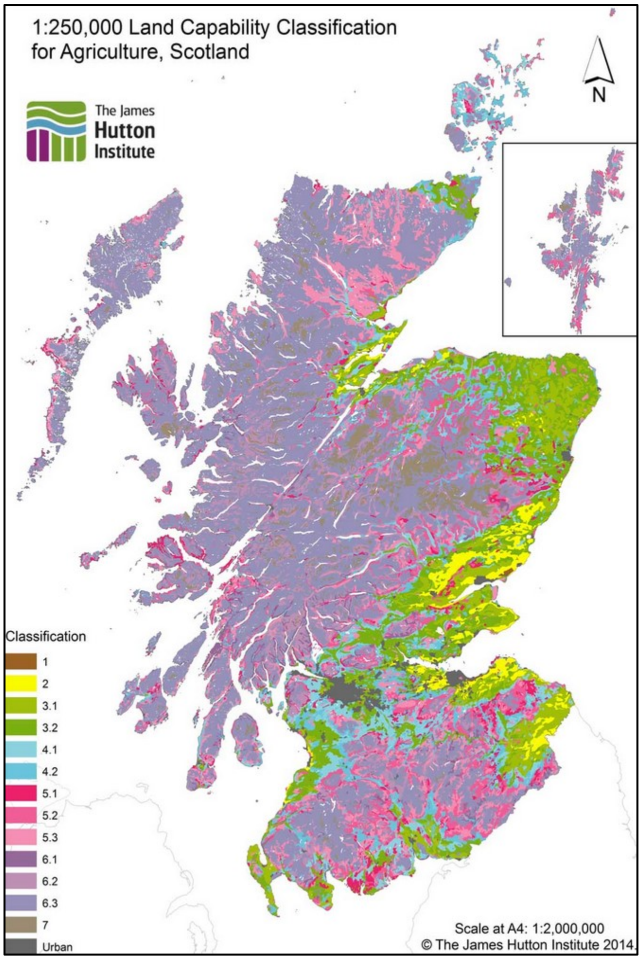

Figure A1 Land Capability for Agriculture in Scotland

As is apparent from the Figure A1, the best agricultural land is concentrated in the lowlands of the east of Scotland, including the Tweed valley, East Lothian, Fife, Angus, Aberdeenshire, as well as the Solway and Moray coasts. Land capability, i.e. the flexibility of production options, generally declines with altitude due to reduced temperature, as well as with increasing rainfall to the west and reduced temperature to the north. In Scotland, these three gradients are associated with poorly draining soils, which further decrease land capability.

For the purposes of this report, marginal land is defined as running from LCA classes 3.2 to 6.1, inclusive (Slee et al., 2014). Class 3.2 differs from 3.1 in having more climatic restrictions on crop growth and a higher risk involved in crop production, though it can still have high profitability if producing malting grade barley. Any division based on land capability is different for different farming systems. The break between 3.1 and 3.2 represents the cut-off between prime land and land marginal for arable agriculture. The most profitable dairy farms are in the band 3.2 to 4.2, with 5.1 and above currently marginal. The chosen cut-off between 3.1 and 3.2 is used as it covers marginal land in its widest sense.

The better marginal land classes also show spatial patterns; class 3.2 is concentrated in Caithness, Aberdeenshire, the Central Belt and Ayrshire, classes 4.1 and 4.2 on the fringes of the Southern Uplands (Figure A1). Classes 5.1 to 5.3 are characteristic of valleys in the hillier parts of Scotland. Classes 6.2, 6.3 and 7 are unlikely to see intensification of land use, though woodland planting may occur.