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The potential risks to water quality from diffuse pollution driven by future land use and climate change

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This document was produced by:

The James Hutton Institute,

Craigiebuckler,

Aberdeen

AB15 8QH

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Executive Summary

Part of the WFD Article 5 reporting requirements is an element of horizon scanning to the middle of this century to identify potential risks to water quality from diffuse pollution driven by future land use and climate change.

A review has been carried out and the key changes that might result from these drivers are an expansion in woodland cover and an increase in the area under arable production as a result of climate change providing enhanced opportunities for agricultural production. These were discussed and agreed at a project workshop and formed the basis of the land use change scenario used in the project. Other potential drivers such as CAP reform, planning and renewable energy development were also reviewed.

A suite of potential pollutants have been classified into groupings according to expected dominant climate drivers (annual and seasonal rainfall) and according to their relationships with different land use types.

The two sets of groupings together form the basis of a qualitative model of risk, and a series of matrices have been developed to translate the various climate and land use change drivers into a set of pollutant responses. A set of climate and land use scenarios based on some of the key drivers identified in the literature review has then been used to explore some possible future water quality responses.

The matrices use a -2 (decrease) to +2 (increase) and describe the relationships between:

(1) key climate change drivers and expected pollutant responses

(2) impact of changing land use on pollutant responses

(3) relative importance of climate change driver versus land use change driver on pollutant responses.

A suite of maps have been produced that show qualitative changes in:

- Seasonal and annual rainfall and potential evapotranspiration
- Run off
- Exported loads of different specific pollutants to water caused by climate change alone (both simulations)
- Exported loads of different specific pollutants to water caused by land use change
- Exported loads of different specific pollutants to water caused by climate change (both simulations) and land use change

The pollutant responses to climate change differ between the two simulations evaluated, and in some cases the predictions operate in different directions (increasing versus decreasing) and are spatially highly variable. In general, the responses, albeit based on a qualitative methodology directed by expert judgement, indicate a deterioration in water quality for the majority of the pollutants, particularly on land currently occupied by improved grassland, the land use type most likely to undergo change under the land use change scenario selected.

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1.0 Introduction

As part of the WFD Article 5 requirements, SEPA are obliged to compile a Significant Water Management Impact (SWMI) Report by March 2013 and the second River Basin Management Plan (RMBP) report during 2014. Included in this process is an element of horizon scanning beyond these dates to identify potential impacts on water quality until the middle of the 21st century. In this context, there is a need to:

- Identify the potential risks associated with two of the high level European and global scale drivers, namely Climate Change and Land Use change on water quality in Scotland.
- Develop a qualitative methodology that identifies whether the impacts of these changes are negative, positive or neutral for a range of pollutants under potential land use and climate change scenarios.
- Produce Scotland-wide maps to identify where impacts might be greatest and more detailed quantitative modelling would be required.

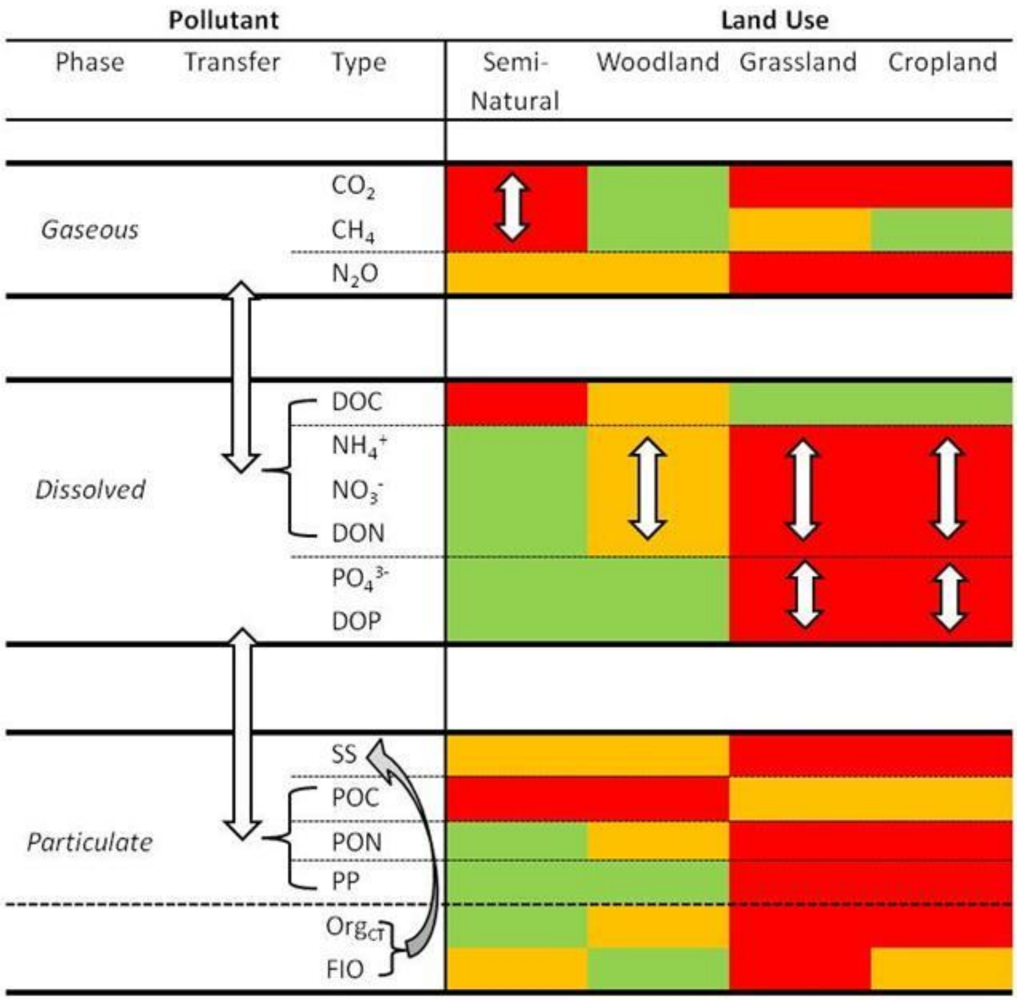
This report presents a literature review and desk study of the climate and land use drivers of pollution and considers possible future scenarios for land use in Scotland. A spatial methodology is then developed for qualitatively exploring the impacts of future climate and land use scenarios on the responses of a range of pollutants. The review and methodology, including proposed scenarios, were presented at a stakeholder workshop and subsequently refined to reflect feedback from participants. The selected scenarios have then been run through the spatial analysis and are presented as a suite of maps and tables detailing a risk assessment for the range of pollutants.

2.0 Pollutant risks associated with broad land use types

Diffuse pollution from rural, mainly agricultural sources, is the main pollution pressure in Scotland today and there is a significant evidence base showing the relationship between land use and management and water quality. Figure 1 summarises the evidence used to assess the qualitative risk of diffuse pollutant production across the four predominant rural land uses in Scotland (Dawson and Smith 2010). This helps define the overall direction that water pollution risk would take should one of these land uses change to another. Within Scottish catchments, where space and topography tend to dictate, a patchwork of different land uses is common and the increased risk of diffuse pollutant production from more intensively managed systems is apparent. Understanding where multiple risks of pollutant production and export occur (i.e. critical source areas – McDowell and Srinivasan 2009) allows for targeted implementation of measures. Quantitatively, diffuse pollutant losses are also influenced by specific hydrological processes and management practices within individual land uses categories. However, these variables are not considered as part of this preliminary assessment, which concentrates on screening for potential risk from given land uses and how these may change in the future. Gaseous emissions from different land uses are not included in the water quality risk assessment but have been considered for identification of potential transport risks from broad land use types as they demonstrate the importance of understanding the whole system in terms of diffuse pollution production and their connectivity within biogeochemical cycles and the potential for pollution swapping.

Figure 1: Potential production and transformations of commonly occurring diffuse pollutants. Qualitative assessment of risks associated with the potential production of individual C, N and P species contributing to diffuse pollution for typical management strategies across the four main land uses (semi-natural, woodland and agricultural: grass/cropland) within the terrestrial landscape ([■] = low risk; [■] = medium risk; [■] = high risk).Adapted from Dawson and Smith (2010). Key: Carbon (CO_2 = carbon

dioxide; CH_4 = methane; DOC = dissolved organic carbon; POC = particulate organic carbon) = Nitrogen (N_2O = nitrous oxide; NH_4^+ = ammonium; NO_3^- = inorganic nitrate; DON = dissolved organic nitrogen; PON = particulate organic nitrogen) and Phosphorus (PO_4^{3-} = inorganic phosphate; DOP = dissolved organic phosphate; PP = Particulate phosphorus) species; suspended sediment (SS); faecal indicator organisms (FIO) and organic contaminants (Org_{CT}), e.g. pesticides.



Estimated emissions of gaseous diffuse pollutants directly to the atmosphere, as C losses or climate forcing greenhouse gases (GHGs – e.g. CO_2, CH_4 and N_2O), have been recently described for different land uses across Europe (Schulze et al. 2010). When combined, European soils are estimated to be a net C sink but act as a net source for GHGs scaled to CO_2 equivalents with croplands, semi-natural upland peatland systems and inland waters the main source categories. Inland surface waters themselves are now considered as important areas for sources of GHGs that can offset terrestrial C sinks, particularly woodlands, grasslands and sediments (e.g. Schulze et al., 2010; Dawson, 2012).Lakes and hydroelectric reservoirs have been shown to be terrestrial hotspots for N_2O emissions and gaseous C cycling (Guerin et al., 2008; Tranvik et al., 2009). Moreover, a significant proportion of the GHGs produced in soils can be transported via the soil-surface waters-atmosphere pathway, e.g. CO_2 and CH_4 in peat dominated systems (Billett et al., 2004; Dawson et al., 2004, Dawson, 2012) and N_2O in agricultural systems (Reay et al., 2009). In *semi-natural* systems, such as peatlands, management through rough grazing, burning or drainage practices as well as for recreational/sporting use and energy generation (peat cutting / wind turbine construction) has led to severe degradation of soils in some areas, increasing C losses from organic-rich soils to the atmosphere as CO_2 and surface waters as DOC and POC through decomposition and erosion processes (Dawson and Smith, 2010). In peatlands and woodlands on organic-rich soils, increased SS from eroded areas can contribute large amounts of particulate organic carbon (POC) to surface waters (Evans and Warburton, 2010). In *woodlands*, impacts on water quality vary greatly dependent on species, site and soil type, and silvicultural practice; native woodlands for example have much less impact than managed coniferous woodlands. Intermittent fertilizer additions and the increased scavenging of atmospheric pollutants (N and sulphur deposition) through forest canopies, increases soil and water acidification and diffuse pollution impacts as N_2O, and soluble forms of N (NO_3^-, NH_4^+) are increasingly exported from woodland systems with increasing throughfall, N-deposition and mean annual temperature (Dise et al., 2009; Sleutel et al., 2009; Dawson and Smith, 2010).

In more intensively managed agricultural systems (*grassland and cropland*), elevated additions of fertilizer and other agrochemicals leads to heightened risk of export of dissolved and particulate N and P and organic contaminants (OrgCT), such as pesticides to water bodies, as well as gaseous emissions of N (Dawson and Smith 2010). Pollutants can be attributed to not only diffuse sources across agricultural landscapes, but also major ‘point’ sources such as farmyards, effluents from milking sheds and slurry/manure storage areas with associated increased exports of pathogens, detected via faecal indicator organisms - FIOs (McDowell and Srinivasan, 2009; Stevens et al., 2009; Kay et al., 2010; Novak and Fiorelli, 2010). Inorganic fertilizers contain readily solubilised forms of N and P, for example, ammonium nitrate, triple superphosphate or urea. Organic-based fertilizers including manure, sewage sludge and composted material produce similar N gaseous emissions and release of dissolved nutrients at rates that are constrained by soil microbial processes (Schulze et al., 2010; Dawson and Smith, 2007) and a potential for pathogenic export.

Soil erosion results in increased mobilisation of suspended solids (SS - a mixture of mineral, organic and colloidal particles) to receiving waters across all land use categories. For water quality, this results in an increased turbidity in receiving waters as well as contributing further to diffuse pollution by exporting sediment-associated components, e.g. particulate phosphorus (PP) and sizeable proportions of FIO, OrgCT and trace metals (Dawson and Smith, 2007, 2010; Stevens et al., 2009; Collins and Anthony, 2008). The episodic nature of SS transport has highlighted the importance of high-flow conditions, e.g. for FIO export to surface waters from improved grassland areas and its associated livestock (Kay et al., 2010). The majority of SS losses occur from catchment source areas with bare or degraded soil structure, increased slope and hydrological connectivity to surface waters. On agricultural land, PP losses occur where there is increased available P (fertilizer or manure applications, farmyard and livestock areas and intensive crop management), often with field drains that connect with watercourses (Stevens et al., 2009).

Other sources of diffuse pollution in rural areas involve private septic tanks and smaller agrochemical usage for amenity value, horticulture and woodland areas. FIO also occur in upland ecosystems but tend to be lower than agricultural areas; they are mainly derived from wild animals grazing proximal to, or drinking from, moorland streams, particularly those in valley bottoms (Kay et al., 2009; Dawson and Smith, 2010).

Figure 1 (Dawson and Smith, 2010) should be viewed as a baseline from which the impacts on water quality from different land use changes might be assessed. For example, a change from arable to woodland will be largely positive with respect to water quality; export of POC is a potential exception to this with dependence on specific management. Similarly some negative responses would be expected with a change from open ground upland habitat to coniferous woodland. However, a change from a low intensity semi-natural habitat to arable production is possibly the biggest potential change should predictions of changes in agricultural capability manifest themselves (Brown et al., 2008).

3.0 Potential future impacts on water quality

The direct impacts of climate change

The UKCP09 database provides the most recent projections for climate change in the UK (Murphy et al., 2009). Key findings of UKCP09 in terms of precipitation and temperature are summarised in Table 1 according to 3 broad regions.

Table 1: UKCP09 key findings showing range of "very unlikely to be less" to "very unlikely to be more" with "central estimate" in brackets for 2050s under the medium emissions scenario (A1(B))

	W Scotland	**N Scotland**	**E Scotland**
Winter mean temp increase	1.0 – 3.0 (2.0) °C	0.6 – 2.8 (1.6) °C	0.7 - 2.9 (1.7) °C
Summer mean temp increase	1.1 – 3.8 (2.4) °C	0.9 – 3.4 (2.0) °C	1.1 - 3.9 (2.3) °C
Winter mean precip	+5 - +29 (+15) %	+3 - +24 (+13) %	+1 - +20 (+10) %
Summer mean precip	-27 - +1 (-13) %	-24 - +2 (-11) %	-27 - +1 (-13) %
Annual mean precip	-7 - +5 (-1) %	-7 - +5 (-1) %	-5 - +5 (0) %

The scale of predicted climate changes is quite uncertain (as reflected by the width of quoted ranges) and caution is urged in interpretation of the UKCP09 data (Street et al., 2009). Analysis of individual model simulations under-pinning the UKCP09 ensemble estimates reveals some key differences in direction and magnitude of response simulated by different model parameterisations. One noteworthy example is inconsistency in the direction of change of autumn precipitation, which can be extremely influential in determining water quality responses (Dunn et al., 2012).

Recent historic weather patterns have pointed towards an increase in the magnitude and frequency of extreme precipitation events (Werritty, 2002, Black and Burns, 2002). Several GCM and RCM studies have indicated that this is a likely impact of climate change for northern Europe (Falloon and Betts 2011). Extreme precipitation events lead to flooding and enhance erosion risks.

Runoff

A changing climate influences water storage and run-off directly. The interplay between two key factors occurs:

1. *Potential evapotranspiration* (PET) rates will increase due to increases in temperature. Changes in other atmospheric variables (e.g. wind speed, humidity) could also influence PET but greater inconsistency in these variables is observed between different climate models, compared with precipitation and temperature (Kjellstrom et al., 2011). Typical estimates of the increase in PET are in the range of +15 - +22% across Scotland. Under the scenario of broadly neutral annual precipitation these figures would cause a reduction in average runoff of -4.4 and -6.7% respectively.
2. However, the uncertainty in precipitation in the future climate simulations is high and for the two specific climate simulations that we have evaluated*, average annual precipitation* was predicted to increase, leading to an overall change in runoff of -0.9 and +8.1%.

An overall guide is that **annual average runoff might be expected to decrease slightly with increases in some regions of the country, but that high uncertainty in precipitation means low confidence can be placed on this statement**. In terms of the usability of water resources it is worth noting that an increase in winter runoff may not translate into a usable water resource unless sufficient storage capacity is available (Falloon and Betts, 2011).

For rivers draining montane catchments an additional impact of climate change is likely to be decreases in the frequency and persistence of snow. Some evidence of changes in long-term seasonal runoff characteristics are believed to be linked to a decrease in snow (Baggaley et al., 2009) and the effects have also been demonstrated through catchment modelling (Dunn et al., 2001). The most identifiable response from these studies is a reduction in spring baseflow. **Given the high inter-year variability that already occurs with regard to snow processes, the overall impact is not considered significant for runoff processes**.

A summer decrease in net precipitation (precipitation minus evapotranspiration) will cause some reduction in summer river flows, but this will be less significant than the projected net precipitation change since summer flows are largely sustained by baseflow generated from winter and spring precipitation. Perhaps more importantly, **the decrease in net precipitation would increase soil moisture deficits** and lead to a delay in the autumn return to field capacity. This is a potential area of concern for agriculture with an increased propensity to drought conditions which could lead to an increase in irrigation demand, especially in the east of Scotland (Brown et al., 2011).

Impacts on pollutant transport and water quality

Nitrogen
Losses of solutes such as inorganic N will be directly influenced by climate change through two principal mechanisms (a) changes in biogeochemical cycling triggered by changes in temperature and soil moisture and (b) changes in leaching and direct surface losses triggered by changes in runoff patterns.

Increases in temperatures might be expected to increase the mineralization of soil organic matter. However this may be offset against effects of modified water availability which are still somewhat unclear. A detailed study of the effect of wetting and drying cycles on mineralization concluded that increasing summer droughts would most likely reduce the mineralization and fluxes of N (Borken and Matzner, 2009). Beier et al (2008) also found that N mineralization was relatively insensitive to temperature increases and was more strongly influenced by changes in soil moisture. In addition to changes in mineralization, de-nitrification and plant uptake could be enhanced by temperature increases and would tend to counteract any increases in mineralization. Increased denitrification in aquatic systems may also be offset by increased N fixation (Jarvie et al., 2012). Overall it seems likely that the complex effects of changing biogeochemical cycles on N losses will be smaller than those triggered by changes in runoff patterns.

Nitrate leaching in Scotland is closely linked to hydrological behaviour with seasonal patterns in losses that can be related to runoff. The highest risk period for N losses is during the autumn and winter. During the summer, any excess of inorganic N over and above plant needs accumulates in the soil until soil moisture levels are replenished by autumn precipitation. High loads of N are then associated with autumn and winter runoff events. **Under a climate change scenario of increased autumn and winter runoff, this could potentially lead to increases in N loads. However, model simulations have indicated that concentrations of N might be expected to remain broadly neutral (Dunn et al., 2012).**

Sediment
The processes that lead to soil erosion and losses of sediment from the catchment are exacerbated by increased winter rainfall, prolonged summer drought and increased frequency of high intensity rain events (Rose et al., 2012). **It is therefore highly likely that the projected climate changes for Scotland will lead to increased sediment losses**.

Phosphorus
Dissolved P tends to dominate total P content during low flow conditions (Ernstberger et al., 2004) and is unlikely to be significantly affected by the projected changes in precipitation. Experimental data have shown that extreme events result in high concentrations of suspended particulate matter, particulate and dissolved P, particularly following dry periods (Stutter et al., 2008). Therefore, in line with the expected increase in sediment losses during winter, **diffuse P loads are also likely to increase**. Jordan et al. (2012) also suggest that wetter winters and drier summers would probably increase stream P concentrations during both storms and baseflow, and would be particularly magnified in those catchments with flashy runoff.

Point sources of P (from e.g. sewage treatment works) remain a key pollutant in many rivers, especially in urban areas. **Reduced summer flows will lead to increases in concentrations of P and other point source pollutants**, assuming constant inputs.

Other Pollutants
The responses of other pollutants to direct climate change impacts are expected to follow similar patterns to those of N for pollutants transported in solution (e.g. DOC), and to sediment for those transported in association with particulate materials (e.g. pesticides, heavy metals).

Impacts of land use change driven by climate change

Land use is directly affected by climate most explicitly in providing the energy for plants to grow, but also indirectly for example in defining the window of opportunity for access to the land. Climate is a key factor in the Land Capability for Agriculture (LCA) classification (Bibby *et al* 1991) and provides the overall context within which other biophysical factors operate. Recent work to investigate how LCA may change in a changing climate (Brown *et al* 2008) has indicated a generally more favourable environment for Scottish agriculture with a potential increase in prime agricultural land. Land use will undoubtedly change and adapt to this changing climate and some of the main responses are described below.

Responses to a changing climate are, by convention, usually distinguished between reactive (autonomous) adaptation and planned (anticipatory) adaptation responses. Different sectors vary in terms of their current emphasis across these response types, based upon their target planning horizons. A key factor is the policy context in which these responses take place but for this assessment we have assumed the current policy background continues and that people behave in the same way.

In *agriculture*, reactive responses dominate and land managers therefore tend to change land use or management depending on positive/negative experiences over recent years. As described above a general improvement in agricultural land capability has been projected for many areas of Scotland by the 2050s (Brown et al., 2008, 2011). Land managers are likely to respond to this in two different ways, depending on their location and quality of land. Firstly, an expansion in prime agricultural land in S and E Scotland is likely to lead to an expansion in cropland because of the higher economic returns that crops generally bring over most livestock-based enterprises. As a result land is likely to be used more intensively for agricultural production. Associated with this intensification is potential expansion of autumn-sown rather than spring-sown crops, the introduction of new crops that are currently climatelimited (e.g. maize, or bioenergy crops), and changes in crop rotations (possibly a shift to larger-scale monocultures). Irrigation demand is also highly likely to increase (Brown et al., 2011). These changes are likely to lead to increased emissions of C, P and N, with possibly greater sediment losses due to soil erosion, so overall a negative effect on water quality. **This scenario of an increased arable area was supported at the project workshop and is likely to be part of a shift to increased cropping across Northern Europe.**

Secondly, there may be important changes in current marginal areas. **Climatic amelioration could allow agricultural 'improvement' to be introduced in these areas with the conversion of rough grazing into improved grassland.** A key factor will be the access to the land at critical times of year to maintain improvements and for livestock management. It is also possible that with wetter winters (and possibly wetter autumns/springs) that intensive land management in some of these marginal areas becomes more difficult, and therefore that they revert to rough pasture, or even that land is abandoned. An increase in the proportion of improved grassland may have implications for changes in C, N and P emissions, depending on the direction of change and the resulting land use. It seems likely that the shift to drier conditions favouring improvement is more likely in parts of the south and east, often fringing the uplands. However, given the current biodiversity agenda and the value of semi-natural habitats for sporting use and recreation, a change in this direction is unlikely. Land abandonment may be linked with 'rewilding' initiatives that restore a greater proportion of semi-natural habitats, particularly valuable peatlands.

By contrast, the Scottish Land Use Strategy, part of the Climate Change (Scotland) Act represents a planned (anticipatory) adaptation response and the forestry sector in particular is much more heavily influenced by this approach.

The Land Use Strategy 'is a strategic framework bringing together proposals for getting the best from Scotland's land resources'. It is a high level document that sets out a number of principles for sustainable land use and a number of proposals, coupled with SG existing policies, aimed at taking forward these principles.

Recent work to progress the aspiration of increased woodland cover as a mitigation option was carried out for the Woodland Expansion Advisory Group (Towers et al 2011). This work recognised that woodland expansion would be most likely in a relatively small part of Scotland (because of policy and biophysical constraints over large parts of the country; this is not to rule out new woodlands on say prime agricultural land, but they would be targeted towards very specific objectives such as water protection and amenity. The full report can be accessed at: http://www.forestry.gov.uk/forestry/infd-8meebv

To date, the most significant progress on the Strategy is the agreement on a 100,000 ha woodland expansion over the next decade (10,000 ha/annum) and the Cabinet Secretary has recently agreed to this proposal from the WEAG. **Although this represents a considerable reduction from the previous target, nevertheless woodland expansion represents the biggest planned and anticipated land use change in Scotland over the next decade.**

A second key proposal of the Strategy is to conserve and where possible enhance soil carbon stocks through appropriate management, in particular on Scotland's carbon rich soils. This is primarily likely to involve the restoration of peat bogs, which is not a land use change in the strictest sense. However, impacts of peatland restoration are likely to be positive for water quality.

Impacts of land use change driven by other pressures

Land Use will also respond to economic and policy drivers including the CAP reform and greening, market forces and a whole suite of other more specific drivers such as renewable energy, waste, planning and biodiversity. The impacts of each are difficult to predict with any precision as they are constantly evolving and the commentary below is a brief summary of the current position.

Potential land use changes and what actually drives them are very difficult to predict and this is perhaps illustrated by referring to a DEFRA report from 2008. Here, the project objective was to provide an assessment of the impacts of current and future policies and initiatives on the farming industry to provide estimates of agricultural land use and management in 2010, 2015, 2020 and 2025. Projections of cropping and livestock were made, for example 'Oilseed Rape area to increase by 30%' and 'Dairy numbers fall by 7%' by 2025 (from 2004). However the rationale for the increase in oilseed rape was as a result of the demand for biofuels. This increase may well happen but will it be driven by that policy driver? Food security and supply has risen up the agenda even since that report was written. The report also describes the potential impact of these changes within the agricultural sector on emissions to air and water.

CAP reform

Current proposals to reform of the CAP recognise the importance of payment for public goods and services. However, the size of the budget, the amount of funding for rural development and how the CAP is implemented in Scotland will ultimately determine the impacts on water quality. One key aspect is the move towards area based Single Farm Payments, compared to the current situation which still reflect the historic subsidy schemes. It should be noted that the introduction of the Single Farm Payment has already led to a large reduction in sheep numbers in some of the most fragile parts of Scotland.

Another aspect of CAP reform are the so called 'greening measures ' and dependent on their final shape, they are likely to affect water quality in some way. Key aspects are briefly discussed below.

Crop Diversification: The proposal is that farmers must grow at least three crops, where their arable land covers more than 3 ha and is not entirely temporary grass or fallow. This measure is designed primarily to address monocultures in places like the Paris basin or the expanding area of maize across large parts of Germany.

Perversely, it may have the unintended consequence of affecting livestock farms in Scotland which don't usually grow three crops. This measure would encourage them to either stop cropping entirely and let their whole farm become permanent pasture or to diversify into three crops when it is counter to the farms biophysical conditions and/or their farm management. If farmers choose the latter, the area of ploughed land will increase and thereby increasing the likelihood of impacts associated with that activity.

Permanent Grassland: This proposal states that farmers must maintain the area of permanent grassland (defined as grassland which has not been rotated to an arable crop in the previous 5 years) declared on their holding in 2014 with 5% reduction permitted.

The measure could have the unintended consequence of more frequent ploughing with associated carbon release and sediment transport or to retain the sward in perpetuity. Neither are desirable outcomes. There is evidence that old swards become less efficient both from a production perspective and a soil carbon storage perspective. This measure might encourage more frequent ploughing of grassland to ‘overcome’ the 5 year rule. This would have implications for water quality and for soil carbon, the very property that it is designed to protect.

Ecological Focus Areas (EFAs): Farmers must devote an area equal to 7% of their eligible hectares, excluding permanent grassland, to EFAs. This measure is likely to have the greatest potential of the three proposals to deliver environmental benefits across Scotland including to water courses. The actual location of EFAs on individual farms will be very context specific but it is highly likely that at least some of the focus will be on the protection of water and its associated ecology and biodiversity.

Renewable Energy

The development and implementation of renewable energy technologies is one of the Scottish Government’s main economic objectives and Scotland’s ambitious GHG reduction targets is helping to stimulate the sector. The Scottish Government published the 2020 Route Map for Renewable Energy in Scotland in June 2011. It presents actions which are focussed on the targets below:

- 100% electricity demand equivalent from renewables by 2020
- 11% heat demand from renewables by 2020
- New target of at least 30% overall energy demand from renewables by 2020
- New target of 500 MW community and locally-owned renewable energy

In terms of land use change and water quality, developments for onshore wind, bioenergy and energy from waste and hydropower may have some implications.

Onshore wind: This sector has been by far the fastest expanding in recent years with a large capacity already delivered and plans for at least a similar capacity to be installed in the short to medium term. Although the space occupied by individual wind turbine and associated infrastructure (roads etc) is quite small, the ecological footprint of wind farms might extend across the entire site through for example its impact on soil hydrology.

Windfarm construction and decommissioning are likely to be the main phases of operation that may impact on water quality. If best practice guidance is adhered to, impacts on water quality should be minimised but even then there is likely to be an enhanced risk of sediment transport as the ground surface is disturbed and the protective vegetation removed. On sites with peat or other organic rich soils, there is also a risk of increased DOC and POC transport.

Bioenergy and energy from waste: Biomass is expected to make a key contribution to the delivery of the Scottish Government's target for 11 per cent of heat to come from renewable sources by 2020. The emphasis in the Route map for this sector is to contribute to renewable heat markets rather than electricity; one of the key actions is to review support for large scale biomass electricity only plant under the Renewables Obligation Scotland. This might have implications for the future demand for feedstock for this market and knock on implications for land use. For example, conversion of land to short rotation coppice (SRC) or forestry (SRF) has been on the agenda for some time with associated implications for water; SRC is known to have a higher water demand than agricultural crops for example.

Hydropower: This sector has been the backbone of Scotland’s renewables for many decades. There remains huge potential for further hydropower development in Scotland (Nick Forrest Associates 2008) which could have implications for flow regimes and ecology, although it does not involve a land use change in the strictest sense.

Biofuel: The transport sector accounts for 29% of all energy use and the Renewable Energy Directive has set a target of 10% of transport fuels from renewable sources by 2020. The Scottish Government appear to be targeting the use of hydrogen or electricity driven vehicles rather than the direct substitution or mixing of fossil fuels with biofuel or biodiesel from agricultural crops. Maize production in Germany for example is growing rapidly in response to the Directive requirements and this trend is causing concern for its effect on biodiversity, soils and water resources. At present, it appears very unlikely that there will be any significant land use change to biofuel or other energy crops.

Scottish Rural Development Programme (SRDP)

The current SRDP is to be replaced in 2014 by a new programme to run until 2020 which will need to align with a proposal on future support for rural development by the European Agricultural Fund for Rural Development (EAFRD).

A number of the proposed measures expressed in this have direct relevance to land use: for example Article 23 Afforestation and creation of woodland, Article 28 Agri-environment Climate and Article 30 Organic Farming. These and others will have an effect on the distribution of land use and management across Europe over this period.

Planning

The planning process has a clear impact on land use in that it determines whether certain activities subject to planning regulations actually take place. This covers areas as diverse as new woodland, wind farms (and individual turbines) and new built development. In this respect it does not set policy for these sectors but can have quite a significant influence on whether and where they take place. In essence it provides a filter to many of the issues previously discussed.

The National Planning Framework for Scotland 2 (NPF2) provides a summary of issues that the planning process has to consider. Key aspects not covered by policies already discussed are the scale, type and location of new built developments, urban regeneration projects and the need for new transport links and the improvement of existing ones. New built development does represent a dramatic change of use and generally, but not always, occurs adjacent to existing built up land. Area increases are of the order of 1200-1500 ha/annum and is widely scattered. Given new measures and higher environmental standards in place, new developments should not have significant deleterious impacts on water quality although extreme and flood events represent a threat due to the increase in the area of hard surface.

The NPF2 also identifies specific important national developments. A number of these involve considerable construction activity with associated ground disturbance and movement of soil and overburden which can cause problems for water quality at a local scale. The national development which differs from these is the Central Scotland Green Network which aims to establish 'A strategic network of woodland and other habitats, active travel routes, greenspace links, watercourses and waterways, providing an enhanced setting for development and other land uses and improved opportunities for outdoor recreation and cultural activity'. The area encompasses much of Central Scotland, from Ayrshire, Inverclyde and Dunbartonshire in the West to Fife and East Lothian in the East. The thrust behind it is social and to create a better working and living environment; in this context, the impacts of habitat changes should be positive to water quality.

The NPF2 also contains a number of 'Spatial Perspectives' which in essence describes the vision to 2030 for each broad region of Scotland and to address spatial issues of national importance which cut across city-region and local authority boundaries. For each region, specific developments are identified whereas the broader aspects identify the attributes of each region that are nationally important. It is difficult to identify how these might contribute to land use change. One exception is the need to accommodate a substantial growth in the number of households in the Edinburgh city region and the Upper Forth area over the next 25 years.

4.0 Methodology for spatial analysis

A methodology for the spatial representation of future impacts of climate and land use change on water quality has been developed, based on the preceding literature review. Key drivers of changes in pollutant response have been identified and used to explore likely pollutant responses to anticipated climate and land use changes.

In the context of the climate change drivers, a suite of different pollutants have been aggregated into a simplified classification (Figure 2) based on their phase (dissolved or solid) and the time of year when they are dominantly transported and therefore impact on water quality. For each pollutant group, two drivers are considered: the overall change in mean annual runoff and the change in either autumn or winter precipitation. Seasonal precipitation has been identified as a key factor in determining losses of pollutants. For pollutants transported in solution, autumn is considered to be the key period. This is due to the effect of soils wetting-up enabling pollutants that have been accumulating in the soil during the summer to be rapidly leached. For pollutants transported in the solid phase, winter is considered the key season when erosion processes most commonly occur. However, for FIOs, because of their die-off rate, pollution is more likely to be driven by autumn rather than winter erosion. Similarly for hydrophobic pesticides, which have a typical half-life of 90 days, the risk from autumn precipitation is likely to exceed that during winter.
In relation to land use change, pollutants have been assigned to one of 5 groups according to their relationships with different land use types as follows:

(i) N, SRP, hydrophilic pesticide (dissolved phase and strongly linked to agriculture)
(ii) SS (particulate transport, not linked to chemical inputs)
(iii) PP. hydrophobic pesticide (particulate transport and strongly linked to agriculture)
(iv) FIO (strongly linked to livestock)
(v) DOC, POC (linked to organic soils)

The two sets of groupings together form the basis of a qualitative model of risk, and a series of matrices have been developed to translate the various climate and land use change drivers into a set of pollutant responses. A set of climate and land use scenarios based on some of the key drivers identified in the literature review has then been used to explore some possible future water quality responses.

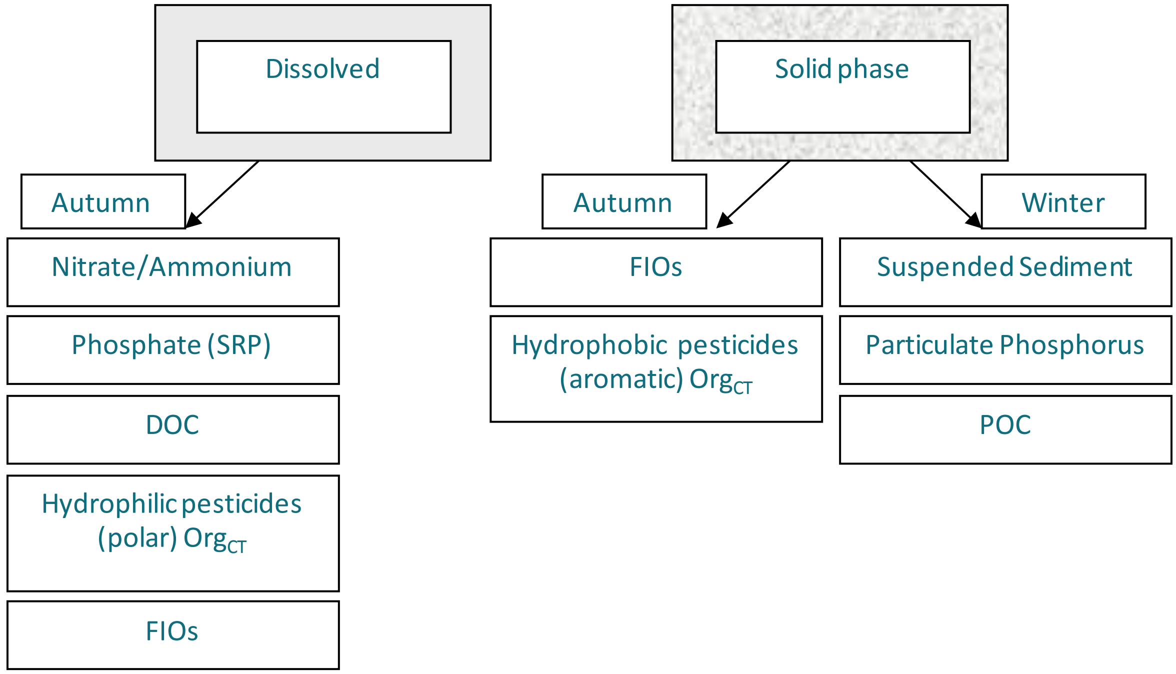


Figure 2 Classification of pollutants according to dominant climate drivers

Development of Matrices
A series of matrices have been developed to describe the relationships between:
(1) key climate change drivers and expected pollutant responses
(2) impact of changing land use on pollutant responses
(3) relative importance of climate change driver versus land use change driver on pollutant responses.

A simplified classification system has been used within the matrices, specifically:
- -2 refers to a large decrease,
- -1 refers to a small decrease,
- 0 refers to neutral,
- +1 refers to a small increase,
- +2 refers to a large increase.

For each pollutant group and driver, values from -2 to +2 have been assigned to the matrix based on expert judgement using both information gleaned from the literature review and basic understanding of runoff processes. Values in the matrices were presented at the stakeholder workshop and subsequently reviewed and refined.

As an example (for illustrative purposes), the table below demonstrates that in response to any climate change scenario, runoff is predicted to increase where there is a rainfall increase and potential evapotranspiration (PET) decrease (+2 in the matrix), and will decrease where there is a rainfall decrease and PET increase (-2 in the matrix). Less pronounced changes in runoff are predicted with smaller PET and rainfall changes (+1, 0 or -1 in the matrix). Matrices have been developed for each of the pollutant response groupings identified in Figure 2, to explain how each pollutant type might be expected to respond to forecast changes in annual runoff and seasonal precipitation. They can be found in Appendix 1.

PET class	Precipitation Change class <-15 ("-2")	-15 - -5 ("-1")	-5 - 5 ("0")	5 - 15 ("1")	>15 ("2")
<-15 ("-2")	-1	0	1	2	2
-15 - -5 ("-1")	-1	-1	1	2	2
-5 - 5 ("0")	-2	-1	0	1	2
5 - 15 ("1")	-2	-2	-1	1	1
>15 ("2")	-2	-2	-1	0	1

Table 2 Assessment of change in annual runoff based on % changes to annual precipitation and PET.

Similar matrices have also been developed for land use change scenarios (Table 3). For example, considering losses of dissolved pollutants (N, P or hydrophilic pesticides), a large decrease is likely with a shift from improved grassland to woodland whereas the opposite holds for land use change in the opposite direction.

Baseline land use	Land use change Arable	Imp grass	Conif forest	B-leaf forest	Semi-nat	Urban
Arable	0	0	-2	-2	-2	-1
Imp grass	0	0	-2	-2	-2	-1
Conif forest	2	2	0	0	0	1
B-leaf forest	2	2	0	0	0	1
Semi-nat	2	2	0	0	0	1
Urban	1	1	-1	-1	-1	0

Table 3 Assessment of impact of dissolved pollutants under different land use changes; cells in yellow are changes that are unlikely to actually occur. This also applies to the land use matrices in Appendix 1.

The matrices were presented at the project workshop and there was a consensus that they were appropriate for the objectives of the project. Some valuable feedback was obtained on the detailed scoring within some of the matrices and they have been subsequently reviewed and adjusted as appropriate.

The matrices enable spatial variability in land use and climate change to be mapped. Within this project two different climate change simulations have been combined with a land use change scenario to explore potential spatial responses of pollutants across Scotland.

Climate and land use change scenarios

The climate simulations used in the analysis were selected from the Met Office's 11 member Perturbed Physics Ensemble, which consists of 11 different parameterisations of a single regional climate model (RCM) called HadRM3. All of these simulations are based on the medium (A1B) emissions scenario.

Working with all 11 simulations was considered to be beyond the scope of this project, so two end members were selected, broadly representing the range of uncertainty encapsulated by HadRM3 (note that this is still smaller than the total range of uncertainty in UK climate projections as a whole, because UKCP09 incorporates a range of different RCMs). The chosen simulations are named HadRM3Q3 and HadRM3Q16, hereafter referred to as Model 3 and Model 16 respectively. As can be seen on the maps in Appendix 2, these two simulations make very different predictions in some parts of Scotland, emphasising the difficulty of incorporating such simulations into an analysis of this kind.

For each of the two model parameterisations, the RCM generates output running from 1950 to 2099, with a daily time step and a spatial resolution of 25km by 25km. These were first interpolated to 5km resolution using statistical downscaling, and then the modelled output for the baseline period (1961 to 1990) was compared to that for the future period (2041 to 2070) in order to derive a series of "change factors" mapping one to the other. These factors were translated onto a qualitative scale (from -2 to +2) consistent with that defined by the matrices.

The selected future land use scenario focuses primarily on the expansion of agriculture and forestry, as outlined by the government's Land Use Strategy for Scotland. The Land Capability for Agriculture 2050 dataset (LCA2050; Brown et al., 2008) identifies areas of the country which may become more suitable for agriculture in the future as a result of climate change. To guide the expansion of agriculture**, we have therefore assumed that all prime land (classes 1, 2 and 3.1) in the LCA2050 dataset is converted to arable by the 2050s**.

For forestry, we have combined the Woodland Expansion Advisory Group Phase 3 dataset (Towers et al, 2011) with the Land Capability for Forestry map (LCF; Bibby et al, 1988) to identify areas of possible woodland expansion. The Scottish Government has a stated aspiration for 25% total forest cover in Scotland, and whilst we recognise that the timeline for this has been recently extended, we assume it is to be achieved by the previous date, the 2050s. **In order to distribute the new trees spatially, classifications in the LCF data were converted sequentially, starting by planting trees on the most favourable land and then including less favourable categories until the 25% target had been exceeded.**

Areas of land not converted either to arable agriculture or to forestry during this process are assumed to be put to the same use in 2050 as they are on the Land Cover Map 2007 (LCM2007; Morton et al, 2011), which is the most up to date national scale land use dataset for Scotland. **Overall, this methodology produces a fairly extreme future scenario, representing the maximum possible extent of both arable agriculture and forestry by the middle of the centur**y. In particular, the area of improved grassland (and therefore of mixed farming) in this scenario is drastically and unrealistically reduced. This is because much of the existing improved grassland is considered to be suitable for arable farming according to LCA2050, and much of the remainder is capable of supporting trees. While these limitations need to be borne in mind when assessing the results presented here, **we feel that the scenario is adequate for a study aimed at exploring the potential impacts of such extremes**. The baseline land cover and the future land use scenario are shown in Figure 3.

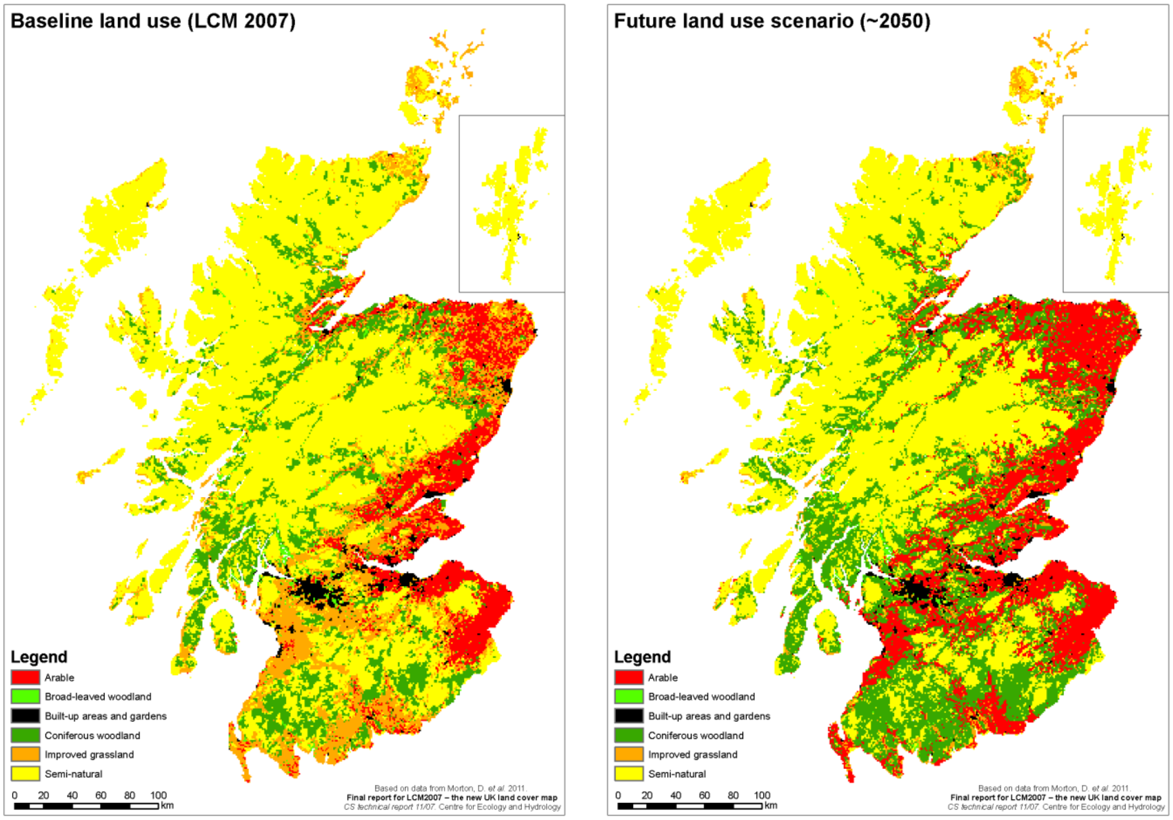


Figure 3: Land use change scenario based on increased arable production and area of woodland cover.

Estimating changes for specific water bodies

The future scenarios have been used, together with the pollutant matrices described above, to yield a set of national scale gridded maps with a cell size of 1km by 1km (see Appendix 2). In an attempt to make this output more relevant to work on Significant Water Management Issues (SWIMIs), we have also summarised the gridded output over each of SEPA's "nested water body catchments". These catchments delineate the total upstream area draining to each of 2,698 water bodies defined by SEPA and monitored as part of the Water Framework Directive.

For each of the 40 output grids, it is possible to derive summary statistics for each nested catchment, giving a broad indication of the changes in pollutant load that might be expected under a given scenario. Because the gridded data is qualitative in nature (on a scale of -2 to +2), we have chosen to estimate the overall catchment-level effect by calculating the modal (most frequent) and median values from all of the 1km^2 grid cells located within each watershed boundary. Due to the fact that the nested catchments overlap one another, it is not possible to plot these summaries on a simple map, but data tables containing all of the calculated statistics have been provided in electronic format.

5.0 Results and Discussion

The full set of maps resulting from the spatial analysis of pollutant responses to the selected climate and land use change scenarios are presented in Appendix 2. Maps 1-8 present data for the two climate change simulations that have been used to drive the various pollutant responses. Maps 9-16 present the pollutant responses to the two climate simulations. Maps 17-22 present the pollutant responses to the land use change scenario. Finally, Maps 23-40 present the combined pollutant responses to both climate and land use change scenarios.

As an illustrative example of the response of one pollutant to this set of scenarios and method of analysis, we have selected to examine the particulate phosphorus response under climate model 3. The principal climate change drivers for PP were identified as the total annual runoff (Map 9) and winter precipitation (Map 3). These drivers combined to generate the CC driven response shown by Map 12, which predicts a moderate increase in PP across much of the country (except the central north) with a large increase along the east coast. The effect of the land use change scenarios on PP is shown in Map 21. Broadly, in areas where land use has been converted into arable land an increase in PP is predicted, and where land is converted to forestry a decrease is predicted. The responses of PP to the combined climate and land use change scenarios are shown by Map 25. This end result broadly indicates predicted increases in PP down the east of the country and the south west and a broadly neutral picture across the remaining area. This occurs because, for the case of PP, the land use driver has been assumed to be more important than the climate change driver in determining loadings of PP and therefore where no land use changes have occurred the pollutant responses are less significant. As a final comment on this example, the significance of uncertainty in the climate simulation can be assessed by comparing Map 25 with the equivalent response resulting from the use of climate model 16, shown in Map 34. The results from climate model 16 are less extreme in terms of the predicted increase in PP, but comparable in terms of the direction of change.

The differences in outputs between the two climate simulations are apparent across the board and highlight a difficulty in handling the uncertainty in climate change for Scotland, because predicted pollutant responses are in some cases in different directions (increasing versus decreasing) and spatially highly variable. In general terms, the responses resulting from model 16 (Maps 14-16) show expected increases in pollutant loads confined to the west coast, but for model 3 (Maps 10-12) much more widespread increases in loads are predicted. In the case of model 3 this follows through from quite extreme predicted increases in autumn precipitation.

It might also be worth reflecting on the impacts of a gross land use change, in this case from grassland to arable. Map 31 shows a projected large decrease in FIO export to the anticipated decline in animal numbers but a large increase in particulate phosphorus due to an increased arable area.

In interpreting the results presented by the maps in Appendix 2 it is worth reiterating that the methodology used to generate the maps is highly qualitative and therefore should only be considered as a relative risk assessment, rather than in absolute terms. Furthermore, the maps represent responses to specific scenarios of land use and climate change. Many alternative future storylines might have been considered, especially in relation to the land use scenario, which could have lead to quite differing outcomes. Equally, different scales could have been used to categorise the pollutant responses and these might have lead to different visual images, especially once the climate and land use change responses have been combined.

Finally, it is worth illustrating how the catchment scale summaries could be used to identify areas where substantial changes in pollutant load might be expected under a given scenario. The accompanying data table *Pollutant_Scores_By_Nested_Catchment.xlsx* gives, for each scenario and each class of pollutant, the modal values for each nested catchment. Each catchment is also assigned a "total pollutant score", which is the sum of all the individual pollutant scores, excluding runoff. Catchments with a high total pollutant score for a particular scenario are therefore those predicted to experience a "large increase" in the load of many different pollutants simultaneously, which may identify them as being “at risk” from a water quality perspective.

However, as before, it is important to bear in mind the variability between scenarios when considering the catchment scale data. For example, the two maps below show those catchments with a total pollutant score of +6 for the scenarios of climate change only. A score of +6 equates to “large increases” in all dissolved and particulate pollutant classes, and it is clear that the situation under model 3 climate is much more severe than that under model 16 climate.

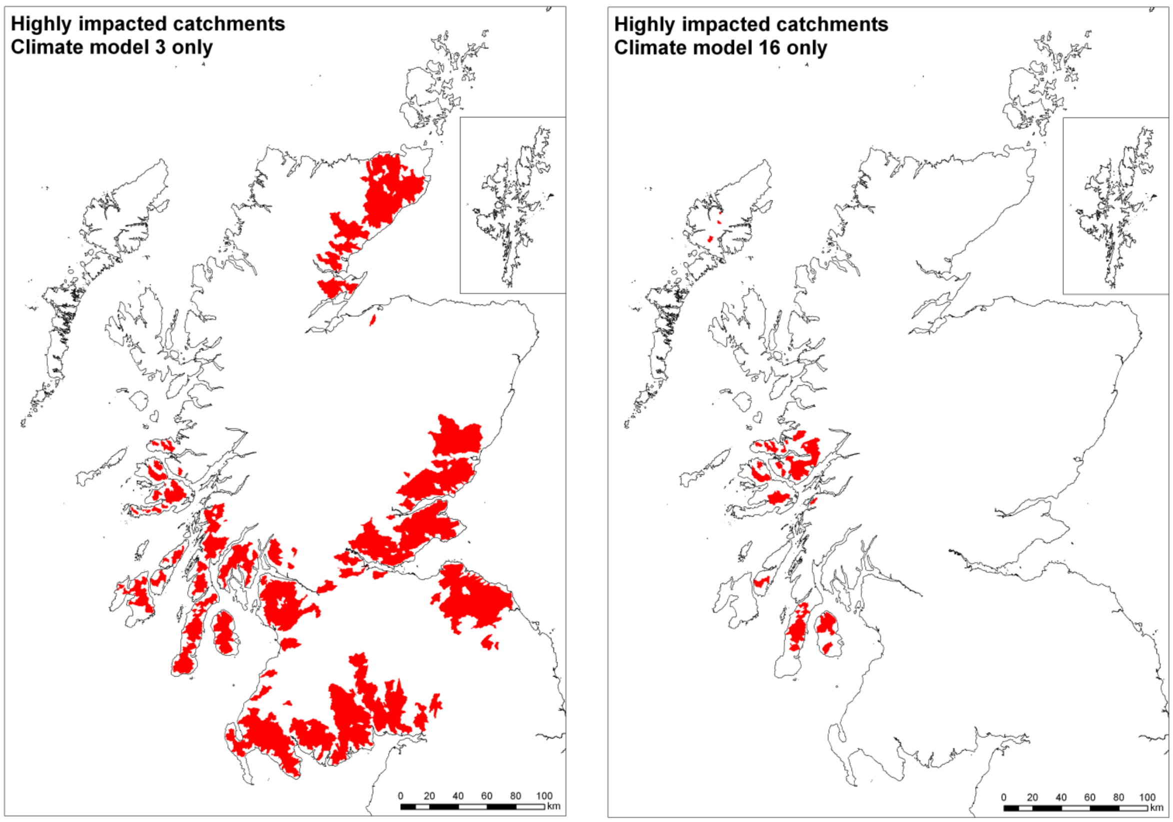


Figure 4: Water body catchments with a high (+6) total pollutant score.

The maps in Figure 4 show the effects of climate change only. Adding in the land use change component has comparatively little impact as large increase in, for example, N (due to arable expansion) is often associated with a decrease in other pollutants like DOC, POC and FIOs (due to a reduction in mixed farming). For this reason, the total scores for the "land use change only" scenario tend to cancel out more than they do with the climate simulations.

6.0 Conclusions and further work

The review of the climate change and land use change drivers strongly suggest that an increase in arable land and in woodland cover will be the principal changes in land use in Scotland until the middle of the 21st Century. Other policies, such as CAP reform, planning and renewable energy developments will also influence land use although their effect is much more site specific or more difficult to predict.

A risk assessment procedure has been applied to two climate change simulations (drawn from one climate scenario) with and without a land use change scenario of increased woodland and arable area. The series of maps produced indicate a range of responses both between the two climate simulations and between the different pollutants. Both of these outcomes are expected; the climate simulations are towards the extremes of the range and different pollutants have different transport mechanisms to water bodies.

The work has proved a very useful screening tool to assess the scale and location of predicted changes in water quality due to climate and land use change. Further work should include a similar assessment using a median climate simulation. Additionally at present, each pollutant is scored equally and it would be useful to explore the impact of different weights being applied to different pollutants. Figure 4 might change as a result if say N had a higher weighting than the other pollutants.

The method has also identified where more quantitative risk assessments are required and provides an initial spatial assessment of critical source areas so that policy and funds may be targeted to higher risk catchments with land uses that have a disproportionate impact on water quality.

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8.0 Appendices

Appendix 1: Matrices used to determine pollutant responses to climate and land use change

(a) Climate change drivers and pollutant responses

Runoff						
		Precipitation Change class				
	PET class	<-15 ("-2")	- -5 ("-1")	-5 - 5 ("0")	5 - 15 ("1")	>15 ("2")
	<-15 ("-2")	-1	0	1	2	2
	-15 - -5 ("-1")	-1	-1	1	2	2
	-5 - 5 ("0")	-2	-1	0	1	2
	5 - 15 ("1")	-2	-2	-1	1	1
	>15 ("2")	-2	-2	-1	0	1

Dissolved Fraction (N, SRP, DOC, FIO, hydrophilic pesticides)						
		Runoff Change class				
	Autumn precip class	-2	-1	0	1	2
	<-15 ("-2")	-2	-2	-2	-1	-1
	-15 - -5 ("-1")	-2	-1	-1	0	0
	-5 - 5 ("0")	-1	-1	0	1	1
	5 - 15 ("1")	0	1	1	2	2
	>15 ("2")	1	1	2	2	2

Particulates (FIO, hydrophobic pesticides)						
		Runoff Change class				
	Autumn precip class	-2	-1	0	1	2
	<-15 ("-2")	-2	-2	-2	-1	-1
	-15 - -5 ("-1")	-1	-1	-1	0	0
	-5 - 5 ("0")	-1	0	0	1	1
	5 - 15 ("1")	0	0	1	2	2
	>15 ("2")	1	1	2	2	2

Particulates (SS, PP, POC)						
		Runoff Change class				
	Winter precip class	-2	-1	0	1	2
	<-15 ("-2")	-2	-2	-2	-1	-1
	-15 - -5 ("-1")	-1	-1	-1	0	0
	-5 - 5 ("0")	-1	0	0	1	1
	5 - 15 ("1")	0	0	1	2	2
	>15 ("2")	1	1	2	2	2

(b) Land use change and pollutant responses

Runoff		Land use change					
	Baseline land use	Arable	Imp grass	Conif fore	B-leaf fore	Semi-nat	Urban
	Arable	0	1	-1	0	1	2
	Imp grass	-1	0	-2	-1	0	1
	Conif forest	1	2	0	1	2	2
	B-leaf forest	0	1	-1	0	1	2
	Semi-nat	-1	0	-2	-1	0	1
	Urban	-2	-1	-2	-2	-1	0

N, SRP, Hydrophilic Pesticide		Land use change					
	Baseline land use	Arable	Imp grass	Conif fore	B-leaf fore	Semi-nat	Urban
	Arable	0	0	-2	-2	-2	-1
	Imp grass	0	0	-2	-2	-2	-1
	Conif forest	2	2	0	0	0	1
	B-leaf forest	2	2	0	0	0	1
	Semi-nat	2	2	0	0	0	1
	Urban	1	1	-1	-1	-1	0

SS		Land use change					
	Baseline land use	Arable	Imp grass	Conif fore	B-leaf fore	Semi-nat	Urban
	Arable	0	-1	-1	-2	-2	-1
	Imp grass	1	0	0	-1	-1	0
	Conif forest	1	0	0	-1	-1	0
	B-leaf forest	2	1	1	0	0	1
	Semi-nat	2	1	1	0	0	1
	Urban	1	0	0	-1	-1	0

PP, Hydrophobic Pesticide		Land use change					
	Baseline land use	Arable	Imp grass	Conif fore	B-leaf fore	Semi-nat	Urban
	Arable	0	-1	-2	-2	-2	-2
	Imp grass	1	0	-1	-1	-1	-1
	Conif forest	2	1	0	0	0	0
	B-leaf forest	2	1	0	0	0	0
	Semi-nat	2	1	0	0	0	0
	Urban	2	1	0	0	0	0

FIO		Land use change					
	Baseline land use	Arable	Imp grass	Conif fore	B-leaf fore	Semi-nat	Urban
	Arable	0	2	0	0	1	1
	Imp grass	-2	0	-2	-2	-1	-1
	Conif forest	0	2	0	0	1	1
	B-leaf forest	0	2	0	0	1	1
	Semi-nat	-1	1	-1	-1	0	0
	Urban	-1	1	-1	-1	0	0

DOC, POC		Land use change					
	Baseline land use	Arable	Imp grass	Conif fore	B-leaf fore	Semi-nat	Urban
	Arable	0	0	1	1	2	-1
	Imp grass	0	0	1	1	2	-1
	Conif forest	-1	-1	0	0	1	-2
	B-leaf forest	-1	-1	0	0	1	-2
	Semi-nat	-2	-2	-1	-1	0	-2
	Urban	1	1	2	2	2	0

(c) combination of land use change and climate change

Runoff, SS - equal weighting						
		Climate Response Class				
	Land use response class	-2	-1	0	1	2
	-2	-2	-2	-1	-1	0
	-1	-2	-1	-1	0	1
	0	-1	-1	0	1	1
	1	-1	0	1	1	2
	2	0	1	1	2	2

N, P, FIO, pesticides - land use dominant						
		Climate Response Class				
	Land use response class	-2	-1	0	1	2
	-2	-2	-2	-2	-1	-1
	-1	-2	-2	-1	-1	0
	0	-1	0	0	0	1
	1	0	1	1	2	2
	2	1	1	2	2	2

C - climate dominant						
		Climate Response Class				
	Land use response class	-2	-1	0	1	2
	-2	-2	-2	-1	0	1
	-1	-2	-2	0	1	1
	0	-2	-1	0	1	2
	1	-1	-1	0	2	2
	2	-1	0	1	2	2

Appendix 2: Mapped outputs from analysis (see separate pdf document)

Map 1: Change in annual precipitation (climate model 3)

Map 2: Change in autumn precipitation (climate model 3)

Map 3: Change in winter precipitation (climate model 3)

Map 4: Change in annual PET (climate model 3)

Map 5: Change in annual precipitation (climate model 16)

Map 6: Change in autumn precipitation (climate model 16)

Map 7: Change in winter precipitation (climate model 16)

Map 8: Change in annual PET (climate model 16)

Map 9: CC driven change in runoff (climate model 3)

Map 10: CC driven change in dissolved fraction (N, SRP, DOC, hydrophilic pesticides) (climate model 3)

Map 11: CC driven change in particulate FIOs and hydrophobic pesticide (climate model 3)

Map 12: CC driven change in other particulates (SS, PP, POC) (climate model 3)

Map 13: CC driven change in runoff (climate model 16)

Map 14: CC driven change in dissolved fraction (N, SRP, DOC, hydrophilic pesticides) (climate model 16)

Map 15: CC driven change in particulate FIOs and hydrophobic pesticide (climate model 16)

Map 16: CC driven change in other particulates (SS, PP, POC) (climate model 16)

Map 17: LUC driven change in runoff

Map 18: LUC driven change in N, SRP and hydrophilic pesticides

Map 19: LUC driven change in FIOs

Map 20: LUC driven change in DOC and POC

Map 21: LUC driven change in PP and hydrophobic pesticides

Map 22: LUC driven change in SS

Map 23: Combined CC and LUC driven change in runoff (climate model 3)

Map 24: Combined CC and LUC driven change in SS (climate model 3)

Map 25: Combined CC and LUC driven change in PP (climate model 3)

Map 26: Combined CC and LUC driven change in N, SRP and hydrophilic pesticide (climate model 3)

Map 27: Combined CC and LUC driven change in dissolved FIO (climate model 3)

Map 28: Combined CC and LUC driven change in particulate FIO (climate model 3)

Map 29: Combined CC and LUC driven change in hydrophobic pesticide (climate model 3)

Map 30: Combined CC and LUC driven change in DOC (climate model 3)

Map 31: Combined CC and LUC driven change in POC (climate model 3)

Map 32: Combined CC and LUC driven change in runoff (climate model 16)

Map 33: Combined CC and LUC driven change in SS (climate model 16)

Map 34: Combined CC and LUC driven change in PP (climate model 16)

Map 35: Combined CC and LUC driven change in N, SRP and hydrophilic pesticide (climate model 16)

Map 36: Combined CC and LUC driven change in dissolved FIO (climate model 16)

Map 37: Combined CC and LUC driven change in particulate FIO (climate model 16)

Map 38: Combined CC and LUC driven change in hydrophobic pesticide (climate model 16)

Map 39: Combined CC and LUC driven change in DOC (climate model 16)

Map 40: Combined CC and LUC driven change in POC (climate model 16)

CREW Facilitation Team

James Hutton Institute
Craigiebuckler
Aberdeen AB15 8QH
Scotland UK
Tel: +44 (0) 844 928 5428

Email: enquiries@crew.ac.uk

www.crew.ac.uk