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Drivers of Biodiversity Loss

A research synthesis for the Tomorrow's Biodiversity Project

BRINGING ENVIRONMENTAL UNDERSTANDING TO ALL

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1 Contents

2 Key findings

This document is a synthesis of current research into, and knowledge of, the drivers of biodiversity loss, both globally and in the UK. Key findings are highlighted below.

- Although biodiversity covers variability in natural systems at all levels, from the genetic, through organismal to ecosystem, biodiversity loss metrics are most often expressed at the organismal level, e.g. in terms of species richness and extinctions.

- Biodiversity is being lost at rates that far exceed any in recent geological history. This loss is anthropogenically driven and is operating at levels which exceed the putative 'safe' levels for mankind.

- Major global drivers in terrestrial ecosystems are:

    - land use change (encompassing habitat loss, degradation & fragmentation);
    - climate change;
    - eutrophication; and
    - biotic exchange (e.g. invasive alien species).

- Major global drivers in freshwater ecosystems are:

    - habitat degradation, including flow modification;
    - pollution, including eutrophication; and
    - biotic exchange (e.g. invasive alien species).

- Major global drivers in marine ecosystems are:

    - climate change (especially in coastal areas);
    - overfishing;
    - habitat degradation (e.g. from destructive fishing operations);
    - acidification; and
    - pollution (including eutrophication of estuaries).

- A number of other drivers are important but do not currently attract so much attention, either because they operate at a local scale, their effects are not currently thought to be so great or their full effects are yet to be realised or understood. These include:

    - Emerging Infection Diseases (EIDs) like Ash Dieback (*Chalara fraxinea*);
    - Water abstraction for agricultural irrigation;
    - Pesticides (e.g. neonicotinoids);
    - Genetically modified organisms; and
    - Sea level rise.

Furthermore new potential drivers, e.g. microplastic pollution, are constantly emerging as issues. Many of these emerging issues can properly be considered as new facets of known existing drivers of change.

- In the UK, the current major drivers of biodiversity loss are generally considered to be:

    - habitat change (broadly equivalent to land use change);
    - eutrophication (and pollution); and
    - overfishing;

  However, it is also recognised that the following two drivers are increasingly important and may become extremely serious in the coming decades:

    - climate change; and
    - biotic exchange (e.g. invasive non-native or alien species).

- At the root of all anthropogenic drivers of biodiversity change are impacts associated with human population growth and increasing per capita consumption.

- The drivers of biodiversity loss are wide-ranging and complex and they interact in ways which we are only just beginning to appreciate, much less understand. Furthermore, the effects of these drivers on biodiversity operate through complex, and relatively poorly understood, ecological processes.

- The Tomorrow's Biodiversity Project should not address itself to unpicking the detail of the links between the complex web of drivers and the response of biodiversity, but rather to observing and recording the effects of drivers on biodiversity to facilitate better understanding and mitigation.

3 Introduction

The Convention on Biological Diversity (CBD) defines biodiversity as: "*the variability among living organisms from all sources including,* inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems*" (CBD 1992). Biodiversity then, by definition, encompasses a huge range of complexity and different levels of organisation in nature, from genes to ecosystems. Typically, we simplify this huge idea by thinking about three broad levels of organisation:

1. genetic;
2. species; and
3. ecosystems.

For most of the last 10,000 years – the Holocene – the earth's environment has been relatively stable but in the period since the industrial revolution – sometimes referred to as the Anthropocene – our actions have started to threaten the very natural systems on which we depend. Rockström et al. (2009) identified nine 'planetary systems' which need to be managed within safe limits for the sake of human health and wellbeing. Of these nine they argued that one in particular, biodiversity loss, is currently running way beyond that safe limit (Figure 1).

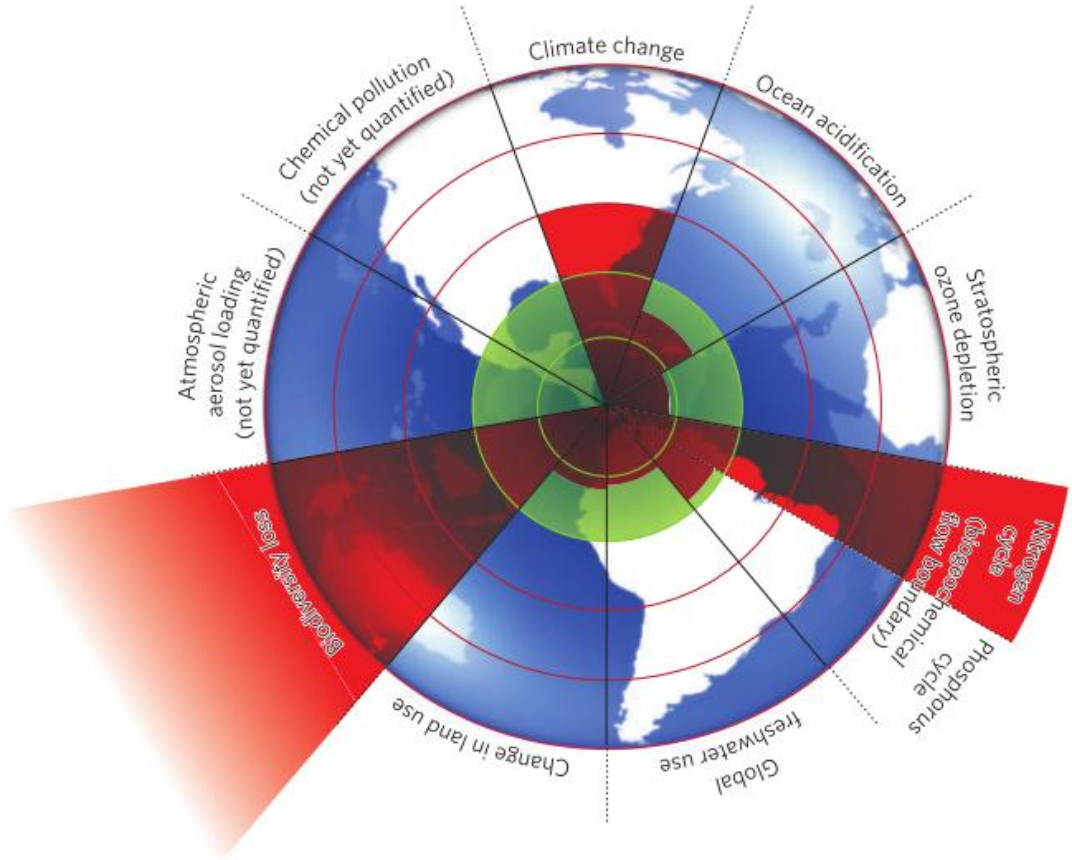

Figure 1. Beyond the boundary. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded. (From Rockström et al. 2009)
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Notwithstanding that quantifying current biodiversity loss is problematic (see below), all of our attempts to do so point to an inescapable conclusion: we are losing biodiversity at a rate unprecedented in recent geological history and many of the drivers behind this loss are anthropogenic. Biodiversity plays a critical part in maintaining the natural systems of the biosphere which are fundamental to human existence on the earth. Recently we have started to think about these systems in terms of 'ecosystem services' and to value the critical role that biodiversity plays in maintaining them (Millennium Ecosystem Assessment, 2005 ; Bailey et al. 2011). Understanding the factors which are driving biodiversity loss is crucial if we are to exercise any control over our future and the health of our planet.

The Tomorrow's Biodiversity Project is focussed on ways in which the Field Studies Council can deliver resources and teaching in ways that maximise its contribution to efforts in the UK to create and manage an inventory of our biodiversity and monitor its health over the coming decades. Doing this in a strategic manner starts with an understanding of the drivers of biodiversity loss globally and here in the UK. This document is a synthesis of current research and knowledge identifying these drivers.

4 Biodiversity Loss

The first difficulty facing ecologists concerned with quantifying biodiversity loss is what to measure – it is not possible to come up with a single metric that encompasses even the three coarse levels of organisation listed above. The easiest things to measure are extent/quality of natural habitat and species richness and these have therefore become the most common metrics used to quantify biodiversity loss (which pretty much ignores the genetic dimension completely).

But even these relatively simple metrics are problematic. For example, how do we measure changes in species richness when we have only named 1.5 million species and estimate that there are between 0.5 and 6.5 million more yet to be found and named? (Costello et al. 2013) How do we measure the extent and quality of natural habitats when there are no universal definitions of what they are, even over a small area like the UK? (JNCC, 2013) How do we do either in our oceans when we have such a poor understanding of what lies therein?

Despite the difficulties, estimating current and predicting future rates of biodiversity loss is an active area of research all over the world. Of habitat extent/quality and species richness/loss, the latter is the most frequently used metric of biodiversity loss. In fact habitat loss – and projected habitat loss – is most often itself used as an input to models which predict rates of species loss. As a level of natural biodiversity organisation which links and, to an extent, spans both the genetic and habitat levels, it makes sense to concentrate on this most tractable, and intuitively meaningful, level of biodiversity organisation.

Nevertheless we should bear in mind that species richness, extinction rates and the other metrics associated with studying biodiversity at the species level can only give us a partial picture of biodiversity loss and the health of ecosystems. There is an emerging theme in the literature reviewed in this synthesis that the effects of drivers of biodiversity change are mediated through ecological processes that are not well-enough understood. Ibáñez et al. (2006) contend that we need a more detailed evaluation and monitoring of ecological processes (e.g. phenology) which are affected by drivers (such as climate change) in order to unpick the detail of biodiversity change. De Chazal and Rounsevell (2009) highlighted a lack of knowledge about processes that determine how species react to drivers – and interacting drivers – of biodiversity change and suggested that this is a major impediment to constructing more useful complex predictive models of biodiversity change. Climate envelope models predicting the response of biodiversity to climate change are very coarse. To improve them, Dawson et al. (2011) advocates synthesising knowledge and information from other sources such as paleoecological observations, recent phenological and microevolutionary responses, experiments and computational models.

4.1 Measures of biodiversity loss

There is unequivocal evidence that current extinction rates of animals and plants are above the natural background rate. Harvell et al. (2002) estimated a loss of 27,000 species per year (based on species/area relationships and land use change). Reaka-Kudla et al. (1996) estimated that rates of anthropogenic driven extinctions are between one and ten thousand times the natural background rate. The range of predicted estimates for future global extinctions from models accounting for climate change and land use change (or combinations of these) drivers is also huge. For example, during the 21st century, predictions are that between c. 0.1% and 50% of all bird species will become extinct, and between 0.2-60% of all plant species (Pereira et al. 2010).

Pereira et al. (2010) explain this variability within and between studies in three ways:

1. uncertainty around the degree of land use change and climate change that will take place;
2. a lack of understanding of the ecology of species and communities and the processes involved in adapting to change; and
3. differences in modelling approaches.

The huge variation and range of estimates reflects uncertainties in scenarios and model parameters, but, despite these uncertainties, there is little room for doubt that anthropogenically driven extinction rates are many times higher than the natural background rates.

In the UK, an unprecedented report was published in 2013 – the result of a collaboration between 25 non-governmental organisations involved in monitoring biodiversity – which, for the first time, presents an evidence-based assessment of how biodiversity, across a wide range of taxonomic groups, has fared in the UK over the last 50 years (Burns et al. 2013). Amongst the headline findings were the following:

- Quantitative assessments of population or distribution trends for 3,148 species indicated that 60% of them have declined over the last 50 years and 31% have declined strongly.

- Half of the species assessed showed strong changes in abundance or distribution, indicating that recent environmental changes are having a dramatic impact on the nature of the UK's land and seas. Evidence also suggests that species with specific habitat requirements are faring worse than generalist species.

- Overall numbers of 155 conservation priority species (selected on the basis of availability of suitable data) have declined by 77% in the last 40 years, with little sign of recovery.

- Of more than 6,000 species assessed using modern Red List criteria, more than one in ten were thought to be under threat of extinction in the UK. A further 885 species were listed as threatened using older Red List criteria or alternative methods to classify threat.

4.2 Extinction debt

'Extinction debt' is the notion that species extinctions lag behind the point in time at which drivers of biodiversity loss cross the thresholds which commit them to extinction. This reflects the idea that there is always considerable inertia in phenomena as complex as the ecological systems into which all species are tightly bound. For example one can think about habitat loss and fragmentation driving reductions in population sizes of a species of butterfly. As the habitat patches in which the butterfly exist become smaller, fewer and further between, there will be a point beyond which the species' metapopulation dynamics are no longer viable, but they will not disappear immediately this point is reached. Rather they will continue to struggle on with inadequate population recruitment and dispersal until they disappear, most likely after some stochastic event – such as a poor summer – finishes them off.

Vittoz et al. (2013) noted that in Switzerland extinction rates may, initially, be lower in the 21st century than predicted by some models due to inertia of ecosystems; local populations may persist through species longevity, restricted dispersal etc., but will be committed to extinction nevertheless.

Extinction debt is an idea that is difficult to investigate empirically, but Dullinger et al. (2013) established that current patterns of biodiversity threat across Europe for six out of seven major taxonomic groups they examined (assessed from national red lists) are better predicted by patterns of economic development in 1900 than patterns of economic development in either 1950 or 2000. (Economic development was used as a surrogate metric for anthropogenic drivers of change.) This suggests that time lags of 100 years between the drivers of biodiversity change and the response of biodiversity many be common. This is worrying because it indicates we may well be living with a considerable extinction debt now.

5 Driver: elevated atmospheric CO_2

By the end of the last century, the concentration of carbon dioxide in the atmosphere was 30% higher than it was before the start of the industrial revolution (Vitousek et al. 1997) and levels are projected to continue this dramatic increase to 2050 and beyond (Schmalensee et al. 1998). Quite apart from the indirect effects of these CO_2 increases operating through climate change (discussed later), elevated CO_2 levels affect ecosystems because of the direct physiological responses of plants to CO_2 levels. The effects of raised CO_2 levels on a plant species depends on the type photosynthetic pathway it exploits and complex interactions with other biotic and abiotic factors including the availability of nitrogen and water in the ecosystem (Mooney et al. 1991; Reaka-Kudla et al. 1996; Sala et al. 2000; Thuiller 2007).

It is clear that the responses of plants to multiple interacting environmental stresses represent a collection of complex phenomena which are extremely difficult to predict. However, Sala et al. (2000) suggested that the variability of the response to this driver amongst biomes would be less variable than their response to any other driver because the strength of the driver itself will be similar over the globe because of atmospheric mixing.

A general prediction made by Mooney et al. (1991) is that middle latitude grasslands (such as those found in the UK) should increase in productivity as a result of elevated CO_2 levels. Sala et al. (2000) predicted that grasslands and savannahs would show most response to elevated CO_2 levels because they are water-limited biomes with a mixture of plants dependent on different photosynthetic pathways. These will react differently to elevated CO_2 levels and therefore alter the dynamics of the ecosystems in these biomes. Thomas et al. (2004) suggested that the direct effects of elevated CO_2 levels will affect ecosystems and result in novel species assemblages, adding uncertainty to predications of biodiversity loss.

6 Driver: ocean acidification

It is estimated that over the last 200 years or so, the oceans have taken up just under 50% of all the CO_2 generated from burning of fossil fuels and cement manufacture (Sabine et al. 2004). Uptake of CO_2 by the oceans results in a decrease in carbonate ion concentration and an increase in hydrogen ion concentration in the ocean; in other words, increasing acidity.

Acidification, particularly of the oceans, does not seem to have received a lot of attention; for example it is barely mentioned in Millennium Ecosystem Assessment (2005). However, it is rapidly climbing up the agendas of those concerned with biodiversity loss and researchers have started to warn of dire consequences for marine coral communities under predicted scenarios of ocean acidification in line with expected increases in atmospheric CO_2 concentrations over the 21st century (Hoegh-Guldberg et al. 2007; Ridgwell and Schmidt 2010). Fabry et al. (2008) reviewed the possible effects of acidification of the oceans on non reef-forming organisms and concluded that there is the potential for wide-ranging changes to marine ecosystems.

Orr et al. (2005) focussed on the likely effects of ocean acidification on shelled zooplankton in the polar oceans. These animals are keystones of the oceanic food-webs and conditions could become unsuitable for them as soon as 2050. Much of our limited understanding of how marine organisms will react to increasing ocean acidification come from laboratory and mesocosm experiments; consequently we have little real understanding of how marine ecosystems will react under 'field conditions' (Doney et al. 2009). Winn et al. (2011) concluded that acidification has major implications for some shell and skeleton forming organisms like corals and that European shelf seas may be vulnerable to increasing acidity.

7 Driver: climate change

Anthropogenic climate change (also known as 'global warming') is driven by atmospheric 'greenhouse gases' such as carbon dioxide, methane and nitrous oxide that have been rising in concentration since the industrial revolution. Increasing levels of carbon dioxide are largely due to the use of fossil fuels and land use change and increases in methane and nitrous oxide are largely driven by agriculture (Intergovernmental Panel on Climate Change 2007). Anthropogenic climate change is generally held to be one of the most serious drivers of biodiversity change.

Bellard et al. (2012) summarises the functional components of biodiversity that are affected by various components of climate change and illustrates that biodiversity is affected by climate change at all levels of organisation from genetic to biome. For example, at a biome scale, there could be an increase in catastrophic events such as flooding or forest fires. At an ecosystem scale the composition and structure, and therefore function, of the ecosystem could be affected. At a community scale, interspecific relationships could be disrupted due to mis-matches between the timing of events e.g. caterpillar hatching and leaf budburst. At a species level, species distribution and range sizes may be affected as climatic conditions change. In terms of populations, recruitment, age structures and sex ratios could all become altered due to changing climates. And, at the scale of individual organisms, changing mutation rates and/or changing evolutionary pressures could lead to genetic changes. These are only some examples; for a more comprehensive list see Bellard et al. (2012).

Table 1. Summary of some of the predicted aspects of climate change. (From Bellard et al. 2012.)

Climate change components				
Temperature	**Rainfall**	**Extreme events**	**CO2 concentrations**	**Ocean dynamics**
Means	Means	Floods	Atmospheric	Sea level
Extremes	Extremes	Droughts	Ocean pH	Marine currents
Variability	Variability	Storms	Ocean	
Seasonality	Seasonality	Fires		

It is useful to categorise the range of responses that organisms can exhibit in response to local climate changes along three axes: spatial, temporal and self (Bellard et al. 2012). Spatial changes can be accomplished by range shifts (e.g. range movements towards the poles) or altitudinal shifts, but also in local shifts to different microclimates. Temporal changes to the timing of significant life history events (phenological changes) or to circadian rhythms, as with spatial changes, can help maintain an organism within its preferred climatic envelope. Changes classified under 'self' include physiological and behavioural changes that shift an organism's climatic envelope to encompass new local conditions. Changes along all of these axes could be mediated through genetic changes over generations or phenotypic plasticity (which can operate within a single generation) – the relative importance of these channels is not currently well understood.

Heller and Zavaleta (2009) listed the following consequences of climate change for biodiversity:

- extinctions;
- range changes (poleward and upward);
- local communities disaggregating and shifting towards warm-adapted species; and
- phenological changes such as earlier breeding or peak in biomass decoupling species interactions.

Range changes and phenological changes are the easiest consequences to observe and a corresponding body of evidence has started to be compiled. For example Wilson et al. (2005) demonstrated that many species of butterfly found in mountainous areas of central Spain have moved their optimum elevation upwards (mean 119 metres) over the previous 30 years. Thuiller (2007) stated that in the Northern Hemisphere terrestrial plants and animals have shifted their ranges, on average, 6.1 km northward or 6.1 m upwards per decade and phenological events have advanced by 2.3–5.1 days per decade over the past 50 years. A four degree rise in temperature over by 2100 (within predicted ranges) could result in a 500 km northward shift or 500 m altitudinal shift for northern hemisphere species. Species living on mountains are thought to be particularly sensitive because of the limited scope for them to move upwards and the fact that as elevation increases, the amount of land available tends to decrease (because of normal mountain topography).

In the UK, there is ample evidence that species are responding to climate change with changes in phenology for birds, plants and other taxa (Sparks & Carey 1995; Crick et al. 1997; Crick & Sparks 1999) and northward movement of range limits (northern and southern), most notably demonstrated for butterflies (Warren et al. 2001) and dragonflies & damselflies (Hickling et al. 2005). The MONARCH project was a major modelling exercise aimed at predicting the distribution of species in Britain and Ireland under climate change scenarios based on bioclimatic envelopes, land cover and dispersal abilities (P M Berry et al. 2005; P M Berry et al. 2007). The results suggest that there will be both winners and losers across a range of taxonomic groups, but the community most likely to suffer is arctic-alpine montane heath. Other sensitive communities include upland hay meadows and lowland beech woods (P. M. Berry et al. 2002; Pam M. Berry et al. 2003; Paula A. Harrison et al. 2003).

In a rare example of a study which attempted to comprehensively investigate the effects of climate change at a national level, Vittoz et al. (2013) catalogued a full range of responses of biodiversity in Switzerland in response to climate change including:

- elevation shifts;
- spread of thermophilous species;
- colonisation by new species from warmer areas; and
- phenological shifts.

In addition, they noted that increasing droughts affected some tree species and warming of freshwater systems in some lowland areas affected fish.

Schweiger et al. (2008) pointed out that range changes could disrupt trophic interactions between species because the potential ranges of interacting species can respond in different ways to climate change. For example climate change may result in a potentially greater range for a butterfly, but if this butterfly is dependent on a food plant which reacts differently – resulting in a lower overlap between their potential ranges – then the actual realised range of the butterfly is likely to contract. Models which rely purely on the bioclimatic envelope of species to predict future range changes probably underestimate this effect.

Sala et al. (2000) predicted that climate change will have the greatest effect on biodiversity in biomes where climate is extreme, such as arctic, alpine, desert and boreal. Here, small changes in precipitation or temperature could have great effects on species composition and biodiversity, but they also noted that climate change could significantly affect all biomes. This is backed up by modelling approaches over Britain and Ireland which have suggested that arctic-alpine montane communities are most at risk here (Berry et al. 2002; Berry et al. 2003; Ellis et al. 2007). Thuiller (2007) asserted that whilst land use change is currently the most serious driver of biodiversity change in equatorial regions, climate change will become relatively more important here over the next 50 years and beyond whilst Malcolm et al. (2006) suggested that species loss could be very significant in biodiversity hotspots – there is currently too much uncertainty around the model assumptions to say one way or another.

On the basis of mid-range climate change scenarios for 2050, Thomas et al. (2004) predicted that 15–37% of species (for their sample of regions and taxa) would be committed to extinction and asserted that it is likely to be the greatest driver of biodiversity loss in many, if not all, regions. Estimates vary enormously, even within single studies, depending on the assumptions of the models; for example estimates of species loss from biodiversity hotspots by Malcolm et al. (2006) varied from less than 1% under the most optimistic assumptions, to 43% under the most pessimistic.

A significant feature of this driver is that even if we were to cap all greenhouse gas emissions right now, global warming would continue for several decades due to the thermal inertia of our oceans Heller and Zavaleta (2009). Understanding this driver and learning to adapt to and mitigate climate change is therefore crucial. The Intergovernmental Panel on Climate Change (IPCC) has predicted a 2.0-6.4 degree Celsius increase in mean surface temperature rise by 2100 compared to pre-industrial levels (Millennium Ecosystem Assessment 2005). Changes in climate over this century are very likely to be greater than at any other time over the previous 10,000 years or more and, combined with other drivers, will limit the capability of species to migrate and their ability to persist in fragmented habitats and have an increasing influence on biodiversity in all major biomes (Millennium Ecosystem Assessment 2005).

It is frequently noted that there may be positive impacts of climate change at a local level. However, overall, there is little doubt that on a global scale, the changes will be overwhelmingly negative (Rinawati et al. 2013). Parmesan and Yohe (2003) noted that, at a local level, the effects of climate change on the abundance and distribution of organisms can be overwhelmed by other factors which act much more strongly at the local scale (e.g. land use change). They took a meta-analysis approach to look for a 'fingerprint' signal of ecological change above this local 'noise' and found overwhelming evidence that climate change is affecting species at a global scale. A number of sources point to synergistic (negatively reinforcing) interactions between climate change and other drivers of biodiversity change (e.g. Reaka-Kudla et al. 1996; Millennium Ecosystem Assessment 2005).

Sala and Knowlton (2006) listed global warming as one of four major drivers of biodiversity change in the marine environment and state that when combined with other disturbances to the ecosystems such as overfishing, the effects of global warming might be more pervasive and unpredictable than previously thought.

Winn et al. (2011) included climate change (and climate variability) as one of the top five drivers of ecological change in the UK but consider that, up until now, it has not had the same level of impact as any of their top three drivers (land use change, direct exploitation of resources and pollution, including nutrient enrichment). However, they predicted that in it will play a significant role in future changes, especially by acting in concert with other drivers.

Overall, Bellard et al. (2012) concluded that neither species loss or the qualitative effects on ecosystem functioning due to climate change can yet be predicted with any confidence. However despite uncertainties, imprecision and both under and overestimation of species loss, the "*very large underestimations due to co-extinctions, synergies and tipping points are extremely worrisome for the future of biodiversity*".

8 Driver: eutrophication (nitrogen & phosphorous enrichment)

Since the industrial revolution our practice of burning fossil fuels has been releasing nitrogen and sulphur into the atmosphere which is then deposited over the surface of the land and sea, sometimes in places very distant from its source. Over the same period, but particularly since the middle of the 20th century, intensification of farming has lead to widespread use of nitrogen and phosphorous fertilizers which get into the wider environment, particularly through rainwater runoff.

The consequence is a general increase in eutrophication over the land and at concentrated points in freshwater and marine ecosystems.

Millennium Ecosystem Assessment (2005) stated that nutrient loading (including nitrogen, phosphorous and sulphur) "*has emerged as one of the most important drivers of ecosystem change in terrestrial, freshwater, and coastal ecosystems, and this driver is projected to increase substantially in the future*". In a wide-ranging synthesis of research on the effects of nitrogen deposition, Bobbink et al. (2010) concluded that it was one of the major threats to plant diversity and 'degradation' in Northern Europe and North America.

Sala et al. (2000) predicted that nitrogen deposition will have the greatest effect on biomes that are nitrogen limited like temperate and boreal forests, arctic and alpine. Other studies have predicted that as developing countries become more important sources of reactive nitrogen, biodiversity hotspots will come under increasing pressure from nitrogen deposition (e.g. Giles 2005; Phoenix et al. 2006). Furthermore, we do not currently understand the mechanisms of Nitrogen deposition impacts in the tropics (Phoenix et al. 2006). Millennium Ecosystem Assessment (2005) stated that nutrient loading will become an increasingly severe problem in all biomes and in developing countries in particular.

Tilman et al. (2001) predicted that agricultural expansion between 2001 and 2050 would result in significant increases in nitrogen and phosphorous fertilization, as well as pollution from increased use of pesticides, all of which will adversely affect biodiversity, particularly in aquatic ecosystems. Dudgeon et al. (2006) identified pollution, including nitrogen enrichment, as a major driver of biodiversity change in freshwater ecosystems and noted that this is especially a problem in freshwater bodies because their position in the landscape so often makes them 'receivers' of wastes, sediments and pollution transported by runoff. Smith et al. (2006) noted that despite huge advances over the last 50 years or more in our understanding of the mechanisms and effects of nitrogen and phosphorous pollution in aquatic ecosystems, 'cultural eutrophication' remains a very significant problem. Monteith et al. (2005) demonstrated that improvements in freshwater chemistry across lakes and streams in the UK are concomitant with improving assemblages of acid-sensitive taxa including epilithic diatoms, macroinvertebrates and aquatic macrophytes.

Among the adverse effects of freshwater and coastal marine eutrophication listed by Smith (2003) are reduced yields of fish, reductions in health of marine coral and changes in species composition of aquatic vascular plants. Sala and Knowlton (2006) listed pollution, especially nitrogen and phosphorus enrichment, as one of the four major drivers of biodiversity change in marine environments. They commented that widespread introduction of excessive nitrogen loads into the marine environment from rivers can results in the creation of 'dead zones' where biodiversity is severely affected.

Atmospheric nitrogen deposition has been shown to have an impact on vegetation in some nitrogen-limited habitats in the UK. Jones et al. (2004) showed that some dune habitats appear to respond to increased nitrogen by producing more biomass which could, ultimately, lead to more soil formation; this could be playing a role in increasing dune stabilisation which we have seen over the last 30-40 years. Stevens et al. (2004) demonstrated a very strong negative correlation between the species richness of British acid grasslands and level of atmospheric nitrogen deposition and found that species adapted to infertile conditions were eliminated in areas of high nitrogen deposition. Stevens et al. (2010) extended this work to show a similar relationship for acid grasslands across Europe.

Maskell et al. (2010) found strong evidence for a negative relationship between plant species richness and nitrogen deposition in acid grassland and heathland habitats in UK, but no relationship for calcareous grassland. Furthermore, they noted that the mechanisms through which these relationships operate are variable, complex and far from clear. For example it seems that increasing nitrogen deposition does not result in more nitrogen becoming available in the soil in acid grassland and heathland and the reduction in species diversity may be a result of increasing acidification arising from the nitrogen deposition. Southon et al. (2013) demonstrated a positive relationship between nitrophilous species and nitrogen deposition for both lowland and upland heathland habitats in the UK and a negative relationship between species diversity (both higher and lower plants) and nitrogen deposition for the same habitats.

9 Driver: land use change

Land use changes range from the dramatic, e.g. conversion of pristine rainforest to palm oil plantation, to the more subtle, e.g. a change from spring to winter-sown cereal crops. As such the driver 'land use change', as used in this document and in most of the literature, encompass both conversion of land to agricultural use and changes in management of existing agricultural land. At the more dramatic end of this spectrum, this is still probably greatest driver of biodiversity change. Wholesale destruction of habitat is itself a quantifiable loss of biodiversity in terms of habitat area, but it is probably more frequently used to quantify biodiversity loss indirectly through by relating it to species extinctions via the species-area relationship (Connor and McCoy 1979).

Reaka-Kudla et al. (1996) stated that habitat destruction is *"by far the biggest problem in protecting the world's biodiversity"* and identified habitat fragmentation as an important aspect of this (as distinct from the overall loss of habitats). Saunders et al. (1991) discuss habitat fragmentation as a natural consequence of land use change and describe the many challenges it presents to the biota which survive in them and to the land-managers charged with maintaining those biota. Dynesius et al. (1994) discusses the extent of 'fragmentation' of riparian systems through damming and diversion and concluded that such fragmentation had significant negative effects on the biodiversity of 77% of the major river systems of the northern third of the world.

A major component of land use change is change attributed to agricultural expansion. Tilman et al. (2001) predicted that the amount of land under agriculture could expand by 18% by 2050 to support a global population stabilising at around 8.5 to 10 billion people. This is equivalent to an area the size of the USA being converted from natural habitats to agriculture and could result in the loss of a third of the remaining tropical and temperate forests, savannahs and grasslands and a consequent "*massive, irreversible environmental impacts*". Under Millennium Ecosystem Assessment (2005) scenarios, 10–20% of grassland and forestland is projected to be converted by 2050 (primarily to agriculture) and this habitat transformation will be a major driver of biodiversity loss.

Another aspect of land use change is agricultural intensification. Reidsma et al. (2006) modelled changes in the biodiversity quality of agricultural land in Europe in 2030 based on the four EURALIS scenarios 2030. In most scenarios, agriculture tends to intensify whilst the total area of agriculture decreases. The latter tends to offset the former, but the overall trend is negative for biodiversity. Butler et al. (2007) stated that the main drivers for the decline of farmland birds in the UK are loss of nesting opportunities and food from the cropped areas of the agricultural landscape. De Chazal and Rounsevell (2009) considered that too much predictive and modelling work concentrates on gross land use changes (conversion of habitat to agriculture or urban area) and ignores equally significant changes to habitat quality.

Land use change to support woody biomass production as bioenergy crops – itself promoted as a way of mitigating climate change by reducing CO_2 production – has itself been implicated as a negative driver of biodiversity change when done in the wrong place or if the complex secondary effects of displacing other land uses is not accounted for (Immerzeel et al. 2013).

Dudgeon et al. (2006) named destruction and degradation of habitat as one of five major drivers of biodiversity change in freshwater ecosystems. This can operate through a variety of interacting factors including direct modification through operations such as extraction of river gravels, and indirect factors such as forest clearance which affects runoff and erosion patterns. They also named 'flow modification' – a ubiquitous phenomenon in freshwater ecosystems – as another of their five drivers, but this could be considered as a particular case of habitat degradation specific to freshwater ecosystems.

10 Driver: direct exploitation

Direct exploitation is often missing from lists of drivers of biodiversity loss (e.g. Sala et al. 2000) but this could be because some reviews address themselves mainly to terrestrial and/or freshwater biodiversity loss. Perhaps another reason is that direct exploitation in terrestrial systems is often addressed as part of land use change.

Direct exploitation has a much higher profile in the marine environment where overfishing is considered to be one of, if not *the* most serious driver of biodiversity change (Millennium Ecosystem Assessment, 2005; Sala and Knowlton 2006). According to Millennium Ecosystem Assessment (2005) about 25% of the world's commercial marine fisheries are overexploited and a further 50% are fully exploited.

Dudgeon et al. (2006) listed over-exploitation as one of the five major drivers of biodiversity change in freshwater ecosystems where it primarily affects vertebrates, particularly fish and amphibians.

Winn et al. (2011) included overexploitation of resources as a major driver of ecological change in the UK in both marine and terrestrial environments. They considered that overexploitation of any of the following can have a negative impact on ecosystems :

- degree of commercial fishing;
- amount and type of timber harvested;
- number of livestock; and
- levels of abstracted water.

11 Driver: biotic exchange (invasive alien species)

Over the last few centuries man has started to move around the planet with increasing ease and rapidity and, in doing so, has introduced a large number of species to areas of the planet that they would not have naturally reached. Some of these introductions have been deliberate, but many more are unintentional (for example those transported in ship's ballast). Many – probably most – of these introductions are benign, but sometimes introduced species are able to exploit a novel ecological situation to the detriment of native species which have not evolved to cope with the new competition and, in such situations, they become problematic and can be a threat to local biodiversity (Vitousek et al. 1996; Reaka-Kudla et al. 1996).

Sala et al. (2000) predicted that biotic exchange will least affect regions that are already highly biodiverse because the biotic and abiotic interactions in such ecosystems limit the opportunities for establishment of new species. Conversely, they predicted that the biomes under greatest threat from biotic exchange are those which are ecologically isolated such as Mediterranean, southern temperate forests and islands. Such areas may host species that exhibit convergent evolution with introduced species which could directly compete with them.

Sala et al. (2000) also noted that biotic exchange is relatively more important in freshwater ecosystems – and lakes more than rivers – than in terrestrial ecosystems due to the higher number of organisms introduced to them (both intentionally and unintentionally). Millennium Ecosystem Assessment (2005) commented that whilst there are increasing measures to reduce biotic exchange along many pathways, freshwater systems are still very vulnerable. Dudgeon et al. (2006) named biotic exchange as a major driver of biodiversity change in freshwater ecosystems.

Didham et al. (2005) considered that invading non-native species are too often identified as the cause of declines in native species through direct biotic interactions (what they termed the "driver model") without enough critical evaluation. They suggested that a plausible alternative explanation of observed correlations between increases in non-native species and declines in native species could be that both are independently correlated to habitat modification by other means. They termed this the "passenger model": habitat disturbance has direct negative effects on native species and exotic dominance occurs by non-natives 'filling the void' even though there can be weak or no direct biotic interactions between the natives and non-natives.

In a controversial comment in Nature, Davis et al. (2011) suggested that too many conservation actions aimed at controlling or eradicating non-native species were not based on the ecological function of those species but purely on their origin. They contested that non-native species generally *increase* the biodiversity in the areas into which they are introduced (excepting the special case of islands and lakes). Countering this viewpoint, Paolucci et al. (2013) reviewed evidence on the effects of introductions of non-native consumers on the abundance of native biota and concluded that non-native consumers generally have greater negative effects than native ones.

Powell et al. (2011) noted that there is still a good deal of controversy surrounding the importance of biotic exchange as a driver of biodiversity change. This might be explained, in part, by the fact that scale is an important factor. Their work suggested that the effects of alien plant invasions are normally greater at local as opposed to regional or global scales. They also suggested that this might be explained if plant invasions tend to affect common native species more than rarer native species.

In the marine environment, biotic exchange is considered to be one of the four major drivers of biodiversity change with ballast water from ships probably being the major vector of transported organisms (Sala and Knowlton 2006). Estuaries are particularly affected and there are examples of rapid invasions of alien species in the marine environment, e.g. some aquatic macrophytes, leading to massive biodiversity loss (Sala and Knowlton 2006).

Winn et al. (2011) considered that the effects of invasive alien species on ecosystems in the UK have not been as great as the other major drivers but expect its influence to grow in the future.

12 Other drivers

The drivers in this section tend to have received less attention that those previously listed. This does not necessarily reflect their relative importance, in some cases it could be because they are only just emerging as drivers or that our understanding of them is only just developing.

12.1 Emerging Infectious Diseases

Emerging Infectious Diseases (EIDs) of wildlife are a significant threat to biodiversity and can cause, or contribute to, both local and global extinctions (Daszak et al. 2001; Harvell et al. 2002; Sala and Knowlton 2006). Chitrid fungus and the effects it has had on many amphibian populations is a well-known example (Daszak et al. 2001). Harvell et al. (2002) noted that there are likely to be very significant synergisms between climate change and pathogens and they noted that pathogens themselves are likely to be sensitive to climate change. They postulated that pathogens are likely to increase the severity of impacts on biodiversity.

Daszak et al. (2001) identified two major drivers of wildlife EIDs:

1. spill-over of pathogens from domestic animals into wildlife populations; and
2. anthropogenic movement of pathogens into new geographic locations — a phenomenon the authors term 'pathogen pollution'.

Daszak et al. (2001) cite parapox virus in Red Squirrels as an example of 'pathogen pollution' (amongst many others).

Harvell et al. (2002) noted that generalist pathogens affecting many hosts could significantly impact biodiversity and that the greatest impacts may come from a small number of EIDs.

Increasing attention is focussing on this driver because of the emergence of serious tree pathogens like *Phytophthora ramorum* ('sudden oak death') – an oomycete pathogen of a number of broadleaved trees including Oak, Beech, Sweet Chestnut and Horse Chestnut – and *Chalara fraxinea* ('Ash Dieback') – a fungus pathogen notably affecting Ash – which could have serious consequences for many taxa which depend on these trees.

12.2 Use of water for agricultural irrigation

Tilman et al. (2001) stated that rising population will result in the demand for water being 1.9 times the 2001 level in 2050. They linked the problems that this will create very closely to those created by increasing phosphorous and nitrogen pollution rather than as a problem in its own right. Millennium Ecosystem Assessment (2005) stated that globally roughly 15–35% of water withdrawals for irrigation are estimated to be unsustainable. Rands et al. (2010) noted that over-abstraction of water for agriculture, industry, and domestic demands contribute to shifts in agricultural patterns with consequent impacts on biodiversity.

This driver may sometime be considered as part of a larger driver. For example, Winn et al. (2011) included water abstraction under their category of 'overexploitation of resources' in the UK National Ecosystems Assessment.

12.3 Pesticides

Pesticides, as a driver of biodiversity loss, received a lot of attention in the past, particularly because of their effects on birds (e.g. Carson 2002; Ratcliffe 1967) but this attention diminished somewhat after legislation was introduced the 1970s and 1980s to control the use of the worst offenders (e.g. DDT). Recently attention on pesticides has started to increase again because their use in intensive agricultural systems has been implicated, amongst other drivers, for the decline in bee populations and diversity (e.g. Potts 2012). The current controversy surrounding the use of neonicotinoids (e.g. Whitehorn et al. 2012) is an example of this.

12.4 Genetically modified organisms

Butler et al. (2007) noted that declines of invertebrates and weeds in the cropped area of fields that is predicted to accompany any introduction of genetically modified herbicide-tolerant crops could have an ecological impact on many farmland birds, though the results of their modelling suggest that this would not be very serious for most of them. It is surprising how few other publications have, to date, dealt with this as a potential threat. Winn et al. (2011) barely mentions them in the UK context, saying only "*it should be noted that considerable concerns exist in some arenas about the potential environmental effects of such technology*".

12.5 Sea-level rise

Rather surprisingly, the effects of sea-level rise on biodiversity rarely seem to be mentioned, but Bellard et al. (2012) pointed out that new projections of a two metre rise by 2100 could have serious implications for coastal and insular biodiversity.

12.6 Horizon scanning

In an annual 'horizon scanning' exercise carried out since 2010 and published in the journal *Trends in Ecology and Evolution*, 15 nascent issues are identified each year that could have an impact on biodiversity (Sutherland et al. 2010; Sutherland et al. 2011; Sutherland et al. 2012; Sutherland et al. 2013). Not all of these issues relate to 'drivers' of biodiversity loss as we have been considering them; for example 'denial of biodiversity loss' (Sutherland et al. 2011) may well emerge as an issue that exacerbates the problem of biodiversity loss but it will not a fundamental driver of it *per se*. Below is a small (and fairly random) selection of the identified issues that might emerge as new facets of existing drivers of biodiversity loss or drivers in their own right.

- Microplastic pollution. Microplastics are tiny (variously defined as under 10 mm down to under 1 mm) fragments of plastic that accumulate especially in the marine environment. It has been estimated that up to 10% of all plastics produced end up here. There is growing concern for the effects that this could have on biodiversity (Sutherland et al. 2010; Cole et al. 2011).

- Nanosilver in wastewater. Nanosilver, also called silver nano-particles, are particles of silver generally less than 100 nm in size. Nanosilver has remarkable antibacterial properties and has been used in many products including textiles and medical applications. Nanosilver can accumulate in tissues and in natural systems via wastewater, but very little attention has been paid to the possible impacts (Chen and Schluesener 2008; Sutherland et al. 2010).

- Use of biochar. Biochar has been proposed as a way to produce energy from biomass whilst emitting less carbon. Biomass is subjected to pyrolysis (rather than combustion) to produce energy *and* charcoal and the latter is buried. If managed correctly, this can result in a net sequestration of carbon (Woolf et al. 2010). On the face of it, this sounds like a promising idea, but concern has been expressed that further loss of primary habitat could occur to produce the biomass required for biochar (Sutherland et al. 2010).

- Applications of artificial life. The creation of new life forms through genetic engineering will become more and more accessible as the technology develops over time. There is a risk that novel genetically created organisms could interact with natural species and even a risk of genetic contamination (Sutherland et al. 2010).

- New greenhouse gases. Nitrogen tri- fluoride (NF_3) and Sulfuryl fluoride (SO_2F_2) are both by-products of human activity (manufacture and agriculture) that have replaced other gasses which are now regulated. Both are rapidly increasing in our atmosphere (though currently at low levels) and are much more 'potent' greenhouse gasses than CO_2 (Sutherland et al. 2011).

- Hydraulic fracturing ('fracking'). Fracking is a relatively new process used to extract natural gas from organic-rich shale deposits. Dangers include groundwater contamination, over-abstraction of groundwater and damage to ecosystems from the physical footprint of the infrastructure needed to support fracking (Sutherland et al. 2011). There is also a very real danger that fracking could significantly lengthen our dependence on fossil fuels thereby countering our efforts to curb CO_2 emissions and weakening drivers to invest in greener technology.

- Methane venting from the ocean floor. There are worrying signs that high-latitude methane deposits in the seabed are being destabilised and released as deep ocean temperatures increase. Methane is a very potent greenhouse gas and this could have very serious irreversible impacts on global climate. Increasing concentrations of methane in parts of the ocean could also deoxygenate these areas (Sutherland et al. 2012).

- Nitrogen fixing cereals. This is a perfect example of a new technology which could be either beneficial or harmful to biodiversity (or both). Creating cereals (by genetic engineering) which have the ability to fix nitrogen (as legumes do) could reduce the need for nitrogen-based fertilisers in agriculture and consequently decrease in the rate of eutrophication of ecosystems which is currently a major driver of biodiversity loss. On the other hand, it might encourage the expansion of agriculture into areas that are currently agriculturally non-productive but which support ecologically important and/or biodiverse habitats (Sutherland et al. 2012).

- The 3D printing revolution. The 3D printing revolution has the potential to change our patterns of manufacture and consumption so fundamentally that it has been described by some as 'the next industrial revolution'. We could see a significant shift to printing (manufacturing) some consumer goods as and when needed (even at home). This has the potential, on the one hand, to reduce environmental damage due to waste and transportation, but, on the other hand, 'printing on a whim' could lead to lead to increases in resource consumption (Sutherland et al. 2013).

- Accelerating water cycle. Increasing global temperatures will accelerate the water cycle with the likely consequences that wet areas will become wetter, dry areas will become dryer, extreme weather events will increase in frequency, saline waters will become more saline and less saline areas will become even less saline. Such significant changes in spatial and temporal patterns of salinity and weather will seriously affect biodiversity (Sutherland et al. 2013).

The participants in these horizon scanning exercises only evaluate issues which, at the time they are considered, are not high in the general consciousness, therefore some issues which are emerging as potential threats to biodiversity (e.g. light pollution) and which are already widely-known are not considered (Sutherland et al. 2012). The breadth of these issues – even the small number considered here – and the uncertainty around their potential effects on biodiversity (sometimes to the extent that we can't even guess if they will, on balance, be positive or negative) is indicative of the uncertainty surrounding the future of biodiversity and our very poor ability to make predictions on how it will fare.

13 Synergies and interactions

Drivers of biodiversity loss seldom operate in isolation from one another as noted by Millennium Ecosystem Assessment (2005): "*Changes in biodiversity and in ecosystems are almost always caused by multiple, interacting drivers*." Interactions between drivers can be 'antagonistic' where their effects are not additive or even tend to work in opposite directions (in which case one may ameliorate the effect of the other) or 'synergistic' they tend to exacerbate the effect of each other (Sala et al. 2000). Sometimes synergistic interactions are described as 'additive' and/or 'multiplicative' (e.g. Brook et al. 2008). Bellard et al. (2012) underlined that most current predictions of biodiversity change ignore the potentially very significant interactions between different drivers of biodiversity loss.

Thuiller (2007) highlighted interactions between climate change, biotic exchange and land use change, in particular, as being both likely and unpredictable. De Chazal and Rounsevell (2009) noted that too many models that attempt to predict biodiversity change concentrate on a single driver such as land use change or climate change. They pointed to the evidence that suggests that these two drivers, and many others, interact in very significant and complex ways. Heller and Zavaleta (2009) stated that climate change works in concert with other drivers of biodiversity change. Thomas et al. (2004) considered that "*many of the most severe impacts of climate-change are likely to stem from interactions between threats*" and stated that habitat fragmentation will hamper species from moving to new climatically suitable areas and competition with invasive species will affect their ability to persist in them.

Hof et al. (2011) reviewed the spatial coincidence of three major drivers of declines in amphibians – climate change, land use change and chitridiomycosis – with spatial patterns of species richness and found that areas with the richest amphibian faunas are, in general, disproportionately affected by a major driver or combination of drivers. They concluded that amphibian declines are likely to accelerate over this century because interacting drivers could affect them more than most studies which have looked at drivers in isolation would suggest.

Studies that model impacts on organisms based on more than one driver are beginning to crop up, for example Gallardo and Aldridge (2013) modelled the response to climate change of two pairs of organisms – in each case one invasive and one native – and discussed projected range changes in terms of how this would affect the biotic interactions between the invasive and native species in each case. Studies like these demonstrate that understanding detailed responses of organisms to drivers of biodiversity change rapidly becomes more complex as one tries to account for a greater number of drivers and interactions between them.

One of the best known synergistic interactions between drivers of biodiversity change is the combination of habitat fragmentation and climate change (Reaka-Kudla et al. 1996; De Chazal and Rounsevell 2009; Vittoz et al. 2013). Reaka-Kudla et al. (1996) stated: "*In the face of climatic change, even natural climatic change, human activity has created an obstacle course for the dispersal of biodiversity. This could establish one of the greatest biotic crises of all time.*" Brook et al. (2008) underlined the importance of reinforcing synergistic interactions between many drivers of biodiversity change but noted, in particular, that climate change interacts with many others such as habitat degradation and overexploitation.

Sala et al. (2000) modelled biodiversity loss by the year 2100 over 10 major biomes under three different scenarios of interaction between drivers of biodiversity change: no interactions, antagonistic interactions and synergistic interactions. For all three scenarios, but particularly that with synergistic interactions, grasslands and Mediterranean ecosystems suffered large biodiversity loss because of their sensitivity to all major drivers of biodiversity change, particularly land use change.

In the marine environment synergies between different drivers of biodiversity change may be very pronounced and change due to individual drivers is hard to disentangle, causing "*changes in biodiversity that are more pervasive than those caused by single disturbances*" (Sala and Knowlton 2006).

In a review of biodiversity change in freshwater environments, Dudgeon et al. (2006) emphasised the high degree of interactions between the five major drivers of biodiversity change that they identified for freshwater environments (over-exploitation, pollution, flow modification, habitat destruction/degradation and invasion by exotic species) and other global drivers such as global warming and nitrogen deposition.

14 Spatial & temporal patterns, trends and relative importance

The relative importance of different drivers, or aspects, of biodiversity change vary depending on ecosystem and biome. Pereira et al. (2010) asserted that land use change is the dominant driver in terrestrial systems and over-exploitation in marine systems with climate change being serious and ubiquitous across realms.

In an influential paper, Sala et al. (2000) reviewed the drivers of biodiversity change across ten terrestrial biomes and listed the following five drivers of biodiversity change for *terrestrial* ecosystems (including freshwater ecosystems), starting with the most important :

- land use change (encompassing agricultural conversion & changes of practice);
- climate change;
- nitrogen deposition (and acid rain);
- biotic exchange; and
- elevated CO_2 levels.

Conspicuous by its absence from this list is direct exploitation, but this is probably because the greatest manifestation of that – overfishing – is an important driver in marine rather than terrestrial ecosystems.

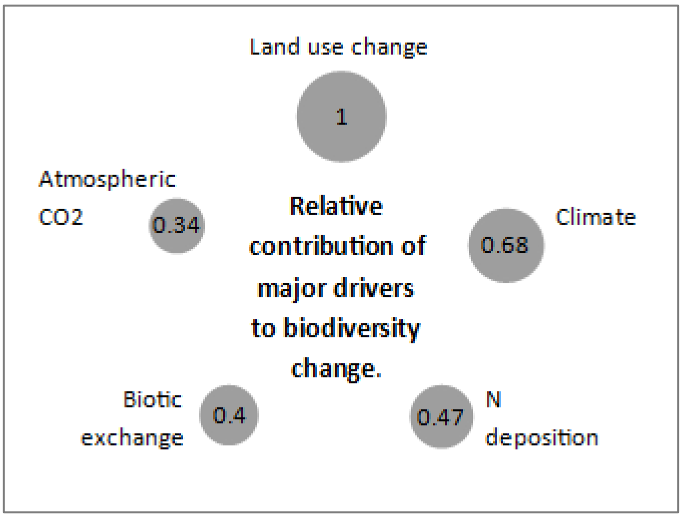

Figure 2. Relative effect of major drivers of changes to terrestrial biodiversity for the year 2100. (After Sala et al. 2000)

The relative importance of these drivers in different biomes has already been alluded to elsewhere in this review, but were summarised very broadly by Sala et al. (2000) as follows:

- tropical and southern temperate forest show large changes in biodiversity mostly driven by land use change;
- arctic ecosystems are largely affected by a single driver – climate change;
- Mediterranean ecosystems, savannahs and grasslands are significantly affected by most of the drivers;
- northern temperate forests and deserts are also affected by most drivers, though to a lesser extent;

- freshwater ecosystems (across all biomes) show substantial changes in biodiversity – perhaps more than any other ecosystem group – driven mostly by land use change, biotic exchange and climate change.

Millennium Ecosystem Assessment (2005) found that the drivers of biodiversity loss thus:

- habitat loss, e.g. through land use change, physical modification of rivers or water withdrawal from rivers, loss of coral reefs, damage to sea floors due to trawling;
- climate change;
- invasive alien species;
- overexploitation of species; and
- pollution.

This is a similar list to that of Sala et al. (2000), with the obvious difference that it does not include CO_2 increases but adds direct exploitation of species.

The figure below is a reproduction from Millennium Ecosystem Assessment (2005) which shows the relative importance of the drivers of biodiversity change over the last 50-100 years and their predicted future influence in different major biomes.

Figure 3. Main direct drivers. The cell colour indicates the impact to date of each driver on biodiversity in each biome over the past 50–100 years. The arrows indicate the trend in the impact of the driver on biodiversity. Horizontal arrows indicate a continuation of the current level of impact; diagonal and vertical arrows indicate progressively increasing trends in impact. This Figure is based on expert opinion consistent with and based on the analysis of drivers of change in various chapters of the assessment report of the Condition and Trends Working Group. This Figure presents global impacts and trends that may be different from those in specific regions. (From Millennium Ecosystem Assessment, 2005.)

As part of the UK National Ecosystem Assessment, Winn et al. (2011) listed the following main direct drivers of ecosystem and ecosystem service change in the UK over the last 60 years:

- habitat change (particularly conversion of natural and semi-habitats through land use change or change in the use of the marine environment);
- nutrient enrichment and pollution of air, land and water;
- overexploitation of terrestrial, marine and freshwater resources;
- variability and change in climate; and
- introduction of invasive alien species.

Note that these are the same five drivers identified by Millennium Ecosystem Assessment (2005) as responsible for driving biodiversity change.

The five drivers are tabulated in a useful figure against the main UK broad habitats to illustrate the relative current effects of each driver against each habitat and predicted future trends in the importance of the driver (see below).

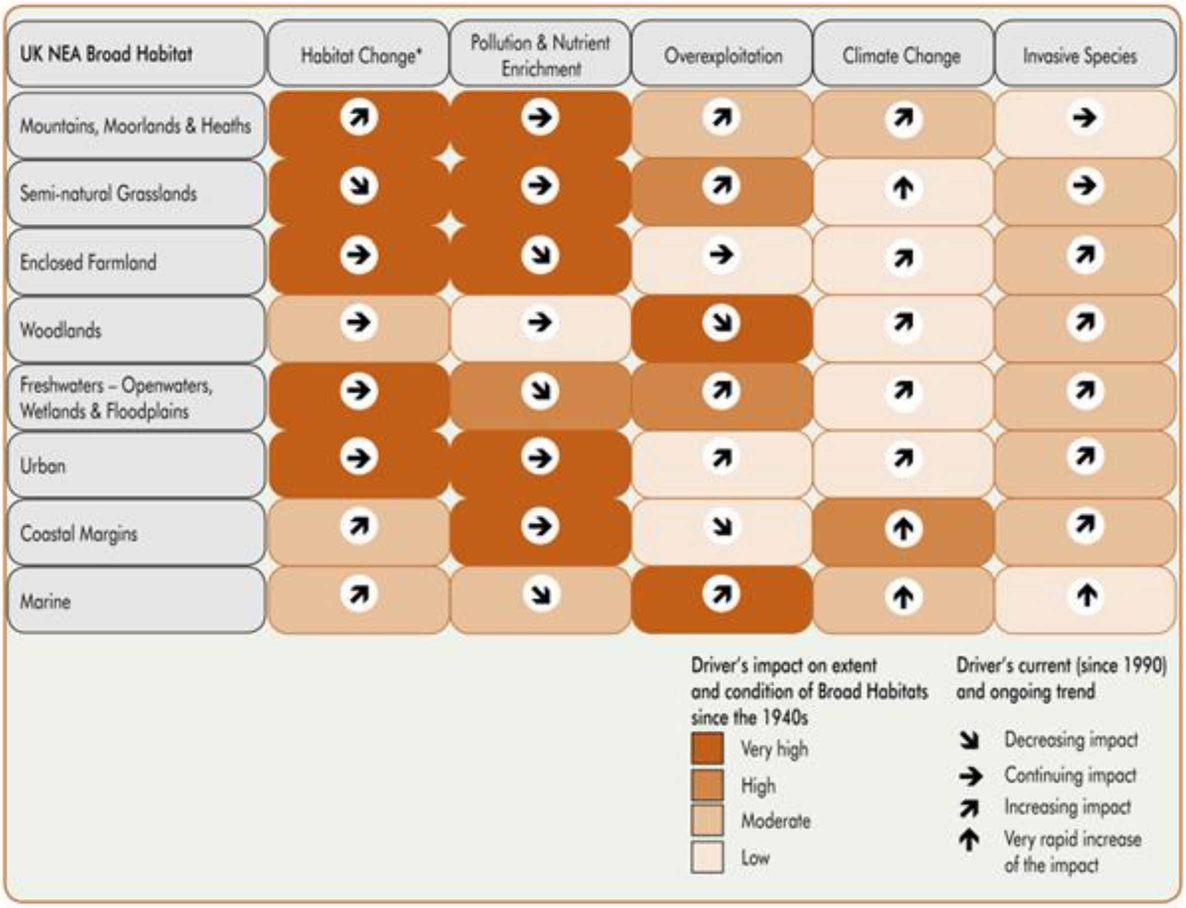

Figure 4. Relative importance of, and trends in, the impact of direct drivers on UK NEA Broad Habitat extent and condition. Cell colour indicates the impact to date of each driver on extent and condition of Broad Habitats since the 1940s. The arrows indicate the current (since the 1990s) and ongoing trend in the impact of the driver on extent and condition of the Broad Habitat. Change in both impacts or trends can be positive or negative. This figure is based on information synthesized from each Broad Habitat chapter of the UK NEA Technical Report (Chapters 5–12) and expert opinion. This figure presents UK-wide impacts and trends, and so may be different from those in specific sub-habitats or regions; however more details can be found in the individual Broad Habitat chapters. *Habitat change can be a result of either land use change or deterioration/improvement in the condition of the habitat. (From Winn et al. 2011, UNEP)

Winn et al. (2011) also tabulated the five drivers against the main UK ecosystem services to illustrate the relative current effects of each driver against each service and predicted future trends in the importance of the driver in relation to the service (see below).

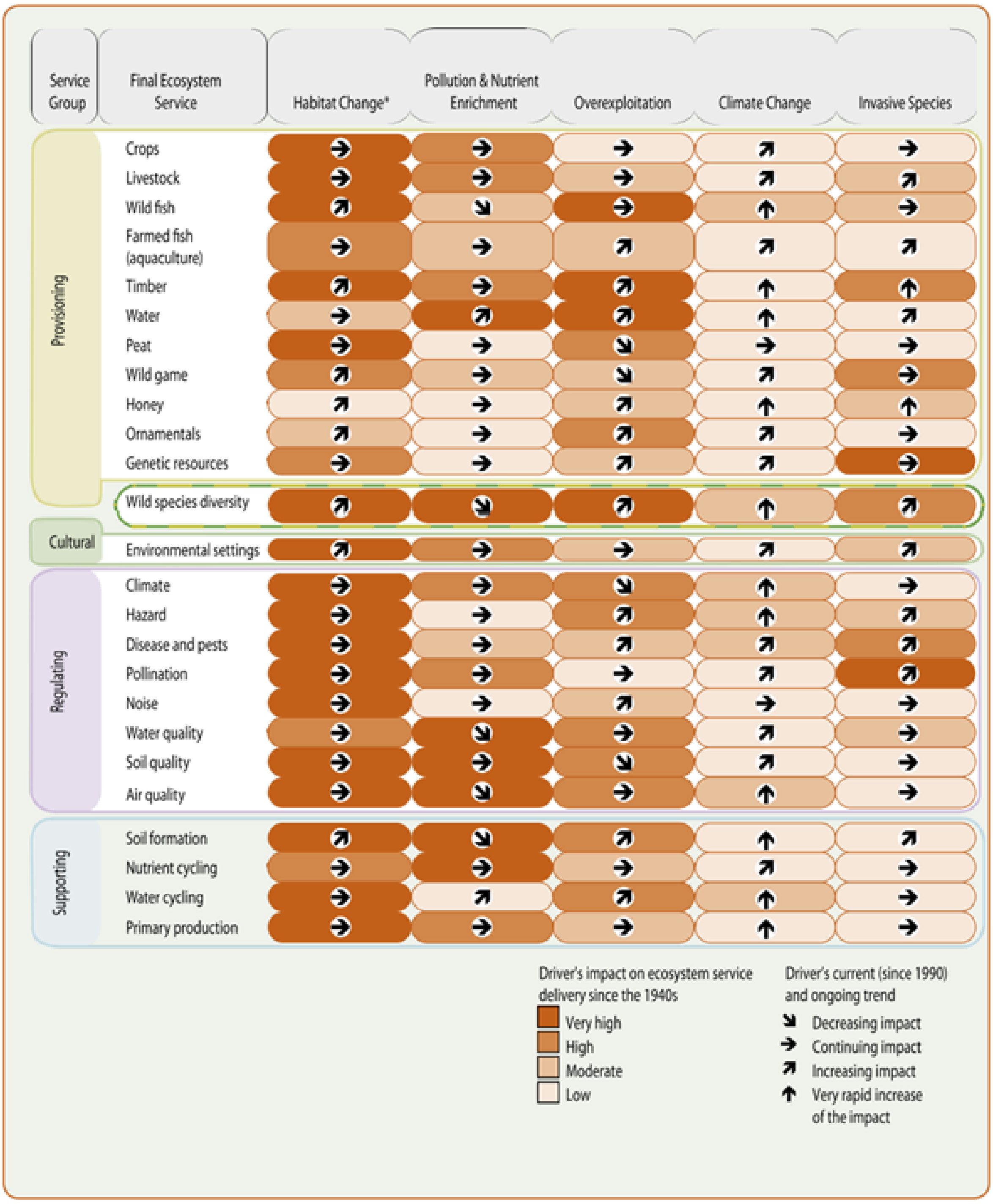

Figure 5. Relative importance of, and trends in, the impact of direct drivers on UK ecosystem services. Cell colour indicates the impact to date of each driver on service delivery since the 1940s. The arrows indicate the current (since the 1990s) and ongoing trend in the impact of the driver on service delivery. Change in both impacts or trends can be positive or negative. This figure is based on information synthesized from the biodiversity and ecosystem service chapters of the UK NEA Technical Report (Chapters 4 and 13–16), as well as expert opinion. This figure presents UK-wide impacts and trends, and so may be different from those for specific final ecosystem services; however more details can be found in the biodiversity and ecosystem service chapters. *Habitat change can be a result of either land use change or deterioration/improvement in the condition of the habitat. (From Winn et al. 2011, UNEP)

An important conclusion of Winn et al. (2011) is that "*there are still significant gaps in our knowledge of what drives ecosystem change and the impacts that changes within ecosystems have on the services they provide*".

Dudgeon et al. (2006) reviewed, in detail, the value of freshwater biodiversity, its continuing loss and the drivers of this change. They listed five major drivers of biodiversity change in freshwater environments:

- Over-exploitation;
- water pollution;
- flow modification;
- destruction/degradation of habitat; and
- invasion by exotic species.

Dudgeon et al. (2006) indicated that all five of these drivers are interlinked, with each individual driver exacerbating, and being exacerbated by, all of the other four. On top of these drivers, environmental changes occurring at larger scales, e.g. nitrogen deposition, temperature changes, and shifts in precipitation and runoff patterns, are superimposed upon all of these (Dudgeon et al. 2006).

Brook et al. (2008) summarised the primary and secondary drivers of extinction as follows.

Primary drivers of extinction:

- habitat destruction & fragmentation;
- overexploitation; and
- pollution.

Secondary drivers of increasing importance:

- climate change;
- environmental variability; and
- invasive species.

Butchart et al. (2010) collated evidence on indicators of the drivers of biodiversity change that suggest that most had continued to increase rather than decrease or stabilise by 2010. These include indicators of:

- deposition of reactive nitrogen;
- number of alien species in Europe;
- proportion of fish stocks overharvested; and
- impact of climate change on European bird population trends.

They noted that global trend data for habitat fragmentation are not available but that it is very likely to be increasing.

Rands et al. (2010) listed the major drivers of biodiversity change as follows:

- overexploitation of species;
- invasive alien species;
- pollution;

- climate change; and (especially)
- the degradation, fragmentation, and destruction of habitats.

Swift et al. (1998) looked, in particular, at the soil nitrogen cycle. They made the following generalisations in regards to this cycle:

- arctic ecosystems are cold limited and particularly sensitive to global warming which will increase decomposition and soil mineralisation rates with consequent (uncertain) effects on soil biota;
- temperate grasslands are nutrient limited and susceptible to increased CO_2 and N-deposition, the net effect of which could be an increase in soil organic matter, though there is little evidence to suggest what effect this will have on the soil biota; and
- tropical rain-forests rely on tightly closed nutrient cycles and are for the foreseeable future more likely to be affected by land use change which has significant impact on soil biota.

The three ecosystems above represent a sequence from high organic soil content and low nutrient recycling (arctic) through to low organic soil content and high nutrient recycling capability (tropical rain forest).

15 Ultimate causes

A distinction can be drawn between direct drivers of biodiversity change (as described above) and other indirect drivers that lie at the root of these. The most commonly cited fundamental drivers are human population increase and increasing consumption per capita (Reaka-Kudla et al. 1996; Martens et al. 2003; Millennium Ecosystem Assessment 2005).

Reaka-Kudla et al. (1996) stated that human population growth runs at 100 million new people every year. Tilman et al. (2001) suggested that population may stabilize at 8.5 to 10 billion people by 2050. A statistic quoted by Sala and Knowlton (2006) is that human population could be 7.5 billion by 2020 with a migration towards the coast.

Martens et al. (2003) suggested that the ultimate forces behind biodiversity loss have three components:

1. economic;
2. socio-cultural; and
3. ecological.

In early stages of socio-economic transition (i.e. in developing counties) social dynamics are the major force behind decline in biodiversity – production and consumption of food, energy, water and fuel reducing ecological capital – whilst in later socio-economical development (e.g. western countries) the major pressures comes from economic dynamics.

Martens et al. (2003) categories have some commonality with five similar categories suggested by the Millennium Ecosystem Assessment (2005):

1. demographic;
2. economic;

3. socio-political;
4. cultural & religious; and
5. scientific & technological.

Sala and Knowlton (2006) noted that human activities are behind all the major divers of marine biodiversity change.

Winn et al. (2011) drew a distinction between the direct drivers of ecosystem change and the indirect drivers which affect these in the UK which they classified as follows:

1. demographic changes;
2. economic growth;
3. socio-political changes, especially in policies;
4. cultural and behavioural changes; and
5. advances in science and technology.

Norton and Reid (2013) recognise five 'ultimate' drivers of biodiversity change in the agricultural landscape which are themselves all drivers of land used change:

1. historical legacies;
2. global climate change;
3. technology and knowledge;
4. markets; and
5. social values and awareness.

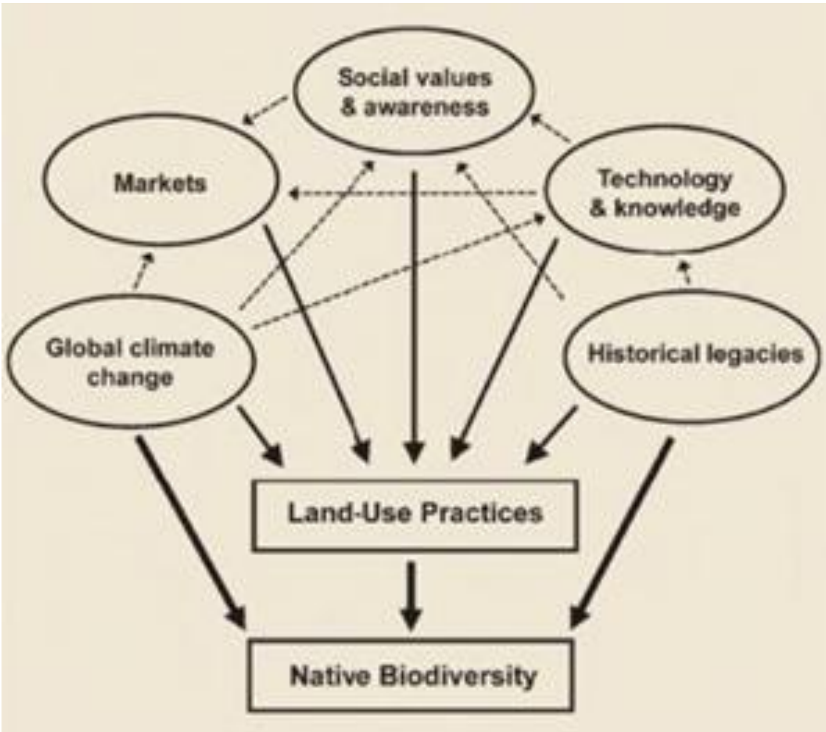

Figure 6. Relationships between different drivers of change and native biodiversity. While all drivers indirectly affect biodiversity through their effect on land use practices (thin black lines), only global climate change and historical legacies directly affect biodiversity (thick black lines). Interactions (dotted lines) also occur among the different drivers. (From Norton and Reid, 2013)

Norton and Reid (2013) asserted that global climate change and historical legacies can affect native biodiversity directly but all five indirectly affect biodiversity by influencing the decisions that land managers make about the way they use their land and water resources and these land management decisions have a range of critical effects on biodiversity. They listed three types of 'historical legacy' as important drivers of change in agricultural landscapes and biodiversity:

1. effects of past land management on soils (e.g. erosion, salinisation, compaction, acidification, nutrient decline, seed-bank loss);
2. ongoing adjustment of the remaining biota to historical fragmentation; and
3. the increasing impacts of invasive species already present but yet to realise their full potential.

16 Concluding remarks & implications for Tomorrow's Biodiversity

The drivers of biodiversity loss are wide-ranging and complex and they interact in ways which we are only just beginning to appreciate, much less understand. Furthermore, the effects of these drivers on biodiversity operate through complex, and relatively poorly understood, ecological processes.

Nevertheless, there is general agreement about the importance of the major drivers of biodiversity change, however their relative importance shifts in different biogeographical realms and in different types of ecosystem (marine, freshwater and terrestrial). There may be some drivers, e.g. ocean acidification, that have been, thus far, underestimated in terms of their importance. Our understanding of the relative importance of drivers that we know of – and new ones that are emerging – is developing all the time.

Major drivers in terrestrial ecosystems are:

- land use change (encompassing habitat loss, degradation & fragmentation);
- climate change;
- eutrophication; and
- biotic exchange.

Major drivers in freshwater ecosystems are:

- habitat degradation, including flow modification;
- pollution, including eutrophication; and
- biotic exchange.

Major drivers in marine ecosystems are:

- climate change (especially in coastal areas);
- overfishing;
- habitat degradation (e.g. from destructive fishing operations);
- acidification; and
- pollution (including eutrophication of estuaries).

The primary purpose of the Tomorrow's Biodiversity Project is to look at the ways in which the Field Studies Council can support national efforts to monitor the state of biodiversity over the coming decades in the face of rapid environmental change. Whilst it is necessary to maintain a strategic overview of the drivers that are affecting that change, it is not the purpose of this project to link particular responses of biodiversity to specific drivers, although whether or not there is scope for monitoring the effects of specific drivers will be revisited, to some extent, in another document that reviews the subject of 'indicators' of biodiversity change.

The main take home message from this review is that drivers operate on biodiversity in diverse ways mediated through ecological processes which are not well understood and normally involving complex interactions with other drivers. The Tomorrow's Biodiversity Project does not address itself to unpicking that complexity – that is the realm of academic research – but rather in observing and recording the outcome of that complex web of drivers in order that they can be better understood and mitigated.

17 References

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