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Ecosystem services and biodiversity in Europe

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building science into policy
at EU level

EASAC

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Foreword

Humankind depends absolutely on what can be delivered by nature in the form of provisions: food, fuel and materials. These are immediately obvious but there are other, less obvious, benefits from nature: the formation of soil and the purification and management of water, for example. Although human intervention plays a role, notably through farming, the provision of most of these benefits from nature is the result of interactions between many species and depends on the working of whole ecosystems. These processes work continuously and unnoticed but are highly effective and have provided sufficient stability for the development of human society. Sadly, we become most aware of them as they fail, as when soil loses its fertility or the failure of pollinators affects agricultural production.

These benefits are known collectively as ecosystem services and we depend for our survival on a wide range of them. As we have become more aware of our dependence and more conscious of the severe pressures that industrial society is placing on their delivery, the health of the ecosystems that provide services to us has become a matter of intense scrutiny, most recently through the UN-sponsored Millennium Ecosystem Assessment.

As the Millennium Ecosystem Assessment makes clear, over the past 50 years the pressure on natural systems has been intense and unprecedented in the history of the world. The human use of natural resources has grown dramatically, land has come under intensive farming or has been taken for towns and cities, and industrialisation has produced pollution that now threatens the world's climate. At the same time, there is a crisis affecting many of the organisms that make up ecosystems. Species are being lost at a rate far higher than natural extinction rates. In addition to direct human impacts on species, invasive species are wreaking havoc on native fauna and flora worldwide and the effects of climate change are beginning to make themselves felt.

The consequence of these human impacts is that we are living through a period in which ecosystems are being degraded and biodiversity is being lost at rates not seen in human history. There are fears that this will have significant consequences for the flow of the services nature provides. We believe that this places Europe's society on an unsustainable trajectory. Failure of ecosystem services will mean, at the least, increasing dependence on imported foods and higher risk from diseases and flooding.

The European Commission has set an aim of halting the loss of biodiversity by 2010. This is an ambitious aim and we applaud it. However, without the recognition of the strong link between biodiversity and the sustainability of Europe's economy and society, we believe that this will be difficult to achieve, particularly in the current economic climate. The link between biodiversity and the delivery of a balance of ecosystem services, which we believe we have substantiated in this report, creates a powerful purpose for measures to prevent further deterioration in Europe's biodiversity.

The Millennium Ecosystem Assessment gives an overview of the state of these ecosystem services at a global level and sets the framework for this study. This report provides a review of the state of ecosystem services in Europe and, crucially, what is known about the contribution biodiversity makes to maintaining them. Our aim is that the report will add to the case for urgent action at a European level to institute a regime of active management for ecosystem services as a whole and to halt the loss of biodiversity.

One of the key messages of this report is that, although European ecosystems can give a wide range of services, managing land primarily to deliver one service will reduce its capacity to deliver other and equally valuable services. This trade-off is particularly important for farming systems, where the intensive use of fertilisers and pesticides may well deliver high levels of food provision but the damage to wildlife may place at risk other important services, such as pollination and nutrient cycling.

We regard the continued delivery of ecosystem services to be one of the most important challenges facing Europe's institutions. We have therefore suggested that there should be a specific duty placed on Europe's governments to manage ecosystem services actively and that there should be a new Directive to ensure this is done systematically and to uniform European standards. We believe that this approach can be combined effectively with existing measures, but we highlight the specific need to ensure the continued delivery of services from Europe's ecosystems.

This report was prepared by an EASAC Working Group led by Alastair Fitter of the Royal Society, London. Many members of the scientific community, within and outside Europe, have contributed to the work, and it has been independently reviewed and approved for publication by EASAC Council. On behalf of EASAC, it is my pleasure to thank Professor Fitter, members of the Working Group and the many experts whose contributions were so valuable in preparing this report.

EASAC will continue to work on the evidence base for action on ecosystem services and biodiversity. We welcome comments on this report.

Professor Volker ter Meulen
Chairman, EASAC

Summary

What are ecosystem services?

Ecosystem services are the benefits humankind derives from the workings of the natural world. These include most obviously the supply of food, fuels and materials, but also such hidden benefits as the formation of soils and the control and purification of water. Ecosystem services are usually divided into categories:

- Supporting services, which provide the basic infrastructure for life on Earth, including the formation of soils, the cycling of water and of basic nutrients, and primary production of materials for all the other services.
- Regulating services, which maintain the environment in a fit condition for human habitation, most notably maintaining a healthy climate and mitigating the effects of pollution.
- Provisioning services, providing food, water, energy, materials for building and clothing, and plants for medicines.
- Cultural services, recognising that people, communities and societies place value (including economic value) on nature and the environment for their own sake or simply find pleasure in them.

Taken together, these services are crucial to survival and social and economic development of human societies on Earth. Though many are hidden, their workings are now a matter of clear scientific record. Their continued good health cannot be taken for granted, and the process of monitoring them and of ensuring that human activity does not place them at risk is an essential part of environmental governance, not solely at a global level but also for the different institutions of the European Union.

One of the key insights from this work is that all ecosystems deliver a broad range of services, and that managing an ecosystem primarily to deliver one service will almost certainly reduce its ability to provide others. One prominent current example of this is the use of land to produce biofuels.

Why do they matter for Europe?

Some of these ecosystem services are crucial for Europe's economy and society.

- Europe is likely to become more dependent on its own ability to produce food as the global price of food increases and imports from outside the European Union (EU) become less affordable.
- Europe will increasingly rely on the cycling of nutrients in soils for maintaining high levels of productivity in both agricultural and non-agricultural ecosystems as the cost and availability of fertilisers in agriculture increases.
- The environment plays the key role in managing water for Europe, in particular in securing the continued availability and regulated supply of clean water against the backdrop of rapid urbanisation and climate change.
- Although the global climate depends on many factors, the services provided by Europe's northern forests and peatlands play a critical role in ensuring long-term storage of carbon.
- Many crops and most wild plant species require the service of pollination by insects; current declines in pollinating insects place at risk a service that would be hugely expensive, and in many cases impossible, to replace.
- Europe's communities place a high value on nature and on the possibility of enjoying natural places for leisure activities.

Other services, though less crucial in a European context, also play an important part in Europe's current prosperity and in ensuring sustainable development in the future. They are considered in this report because the citizens of Europe also have a global responsibility to act in ways that safeguard human well-being and the integrity of the natural environment.

What is their current status in Europe?

In Europe, the trend over the past century has been towards urbanisation and more intensive agriculture. Large areas have been devoted to monocultures, with increasing use of fertilisers, fungicides and pesticides to maintain productivity. This process has prioritised production services, to the extent that other key services, in particular those associated with complex ecosystems or high biodiversity, have suffered. Soil carbon stores have declined, with implications for climate regulation, and loss of species-rich lowland grasslands and wetlands has reduced biodiversity in many parts of Europe. The long-term consequences of this are likely to be severe. Sustaining production levels without recourse to natural processes for nutrient cycling and disease and pest regulation will be increasingly difficult and costly. Similarly, urban and other environments heavily influenced by humans deliver a very restricted range of ecosystem services. Europe's governing institutions have to address

the balance between ecosystem services as a matter of high priority.

What is the link between ecosystem services and biodiversity?

The delivery of ecosystem services depends in many cases on the maintenance of biodiversity, for example for nutrient cycling, production under low-input management and pollination. However, in many instances we do not well understand the mechanism by which biodiversity enhances the delivery of ecosystem services. Small-scale experiments can often explain why the number of species in an ecosystem can determine the rate of the processes that underlie ecosystem services, such as decomposition which is central to nutrient cycling. However, our knowledge of how these processes work together on the scale of a landscape to produce ecosystem services on that scale is limited. It is likely that key species or groups of species that perform particular ecological functions play the major role in delivering services, and maintaining biodiversity is a sure way to ensure their presence and activity in an ecosystem.

How can we place value on these services?

These services cannot be valued unless they are effectively described and properly recognised in decision-making, to ensure that there is at the very least a narrative of what is at stake in decisions affecting them. More powerful means of ensuring that the value of ecosystem services is recognised in decision-making include economic valuation methods. These have developed rapidly in recent years in response to policy-makers' requirements for analysis of costs and benefits of a wide range of development projects. There are now many different and widely accepted ways of placing an actual monetary value on features of the natural environment, using the framework of ecosystem services as a basis. For example, a value for a wetland or a forested catchment can be calculated from the health or water treatment costs avoided through the service it provides in purifying water. In many cases the value of a threatened ecosystem greatly outweighs the development value of the project that threatens it. In addition to these quantitative approaches, there are formal qualitative methods for setting priorities for the use of ecosystems. For example, multi-criteria analysis is a structured approach for assessing alternative options that allow the attainment of defined objectives or the implementation of policy goals in which scoring, ranking and weighting are used. Both quantitative and qualitative methods have been widely applied and are increasingly recognised in policy development and in decisions on individual projects.

What steps are needed to manage ecosystem services now and in the future?

To manage ecosystem services, decisions on the use and management of natural resources, including land and water bodies, have to take account of the full suite of ecosystem services. This will mean balancing productive uses with use associated, for example, with nutrient cycling, which may require reduced cultivation, water cycling (which may require permanent vegetation cover) and management regimes that conserve and enhance biodiversity.

In order to regulate the optimisation of ecosystem services and to protect the role of biodiversity in forming and maintaining them, we propose a new European Directive, building on current legislation, to protect ecosystems and wildlife, with a broad scope and a specific focus on ecosystem services. A new directive of this kind could be expected to establish the strategy of conservation and management of important ecosystem functions and services in Europe. It could also set priorities by defining the 'key ecosystem services of Community interest' and 'key service providing units (species and ecosystems) of Community interest'.

1 Introduction

1.1 Biodiversity and ecosystem services: why this topic matters now

The past 50 years have seen an unprecedented human impact on natural systems (Vitousek et al. 1997). Though evidence is incomplete, current rates of species extinction are believed to be much larger than background or natural extinction rates, and ecologists are concerned that we are witnessing the sixth great extinction wave on the planet. For example, 12% of bird species, 23% of mammals, 32% of amphibians and 25% of conifers are now threatened with extinction (IUCN 2004), and data are simply not available for many other less well-studied groups which may be equally (or more) vulnerable. Human use of natural resources has grown substantially in this period. Roughly half of useable terrestrial land is now devoted to grazing livestock or growing crops, the expansion of which has been at the expense of natural habitat, and between a quarter and a half of all primary production is now diverted to human consumption (Rojstaczer et al. 2001). Since agriculture began in earnest, some 8000 years ago, the area of forest has been halved.

In addition to habitat conversion, other major threats to biodiversity include the introduction of non-indigenous species, pollution, climate change and over-harvesting. On many islands, such as Hawai'i and New Zealand, introduced species are the major cause of extinction, and islands often host large numbers of endemic species, the result of long periods of isolation and evolution. Europe has very large numbers of introduced species; some are known to threaten indigenous biodiversity, but many ancient introductions are now accepted members of the fauna and flora of Europe. Pollution can be a major cause of the local extinction of species, for example by the deposition of nitrogen from the atmosphere causing eutrophication and allowing species capable of a vigorous growth response to nitrogen to outcompete slower-growing species. However, pollution will rarely cause the complete elimination of species unless imposed over very large areas or affected species are rare and have local distributions. The principal example of global-scale pollution is the rapidly increasing concentration of carbon dioxide and other greenhouse gases in the atmosphere, which is driving climate change. So far, there is little evidence of extinctions having already been brought about by climate change, but that situation is unlikely to persist: models that take into account the tolerance of species to climatic factors and the likely rates of environmental change predict that large numbers of species, probably in the hundreds of thousands, will be threatened with extinction by 2050 (Thomas et al. 2004; Pounds et al. 2006).

These large-scale changes in the biological components of the planet will be viewed as inherently undesirable by many and will certainly alter the appearance of many areas. The broader consequences of large-scale losses of species remain uncertain, because the underlying science that links biodiversity – the biological richness of an ecosystem – to the way in which it functions has only recently become a major focus of research. However, there is a growing appreciation of the importance of the natural world to human society. Quite apart from the importance of landscape and biodiversity in a cultural sense and for recreation, direct economic benefits are drawn from natural systems. Some of these are both of major economic significance and essential to the survival of human societies.

The benefits to humankind that can be delivered by natural systems are known as ecosystem services. They include the provision of food, clean water, a stable climate, biological resources for energy and industrial processes, and the control of disease, all of fundamental value to human societies and irreplaceable by artificial alternatives. A large-scale assessment of ecosystem services, made by an international group of scientists and published as the Millennium Ecosystem Assessment, grouped the services into four categories: supporting, provisioning, regulatory and cultural services (see www.millenniumassessment.org and Chapter 2). This categorisation encompasses ecosystem goods like food, medicines and fibre, but also services like water purification, nutrient retention, climate regulation and cultural services like recreation.

The services are provided by living organisms interacting with their environment: this complex of relationships between organisms and environment is known as the ecosystem. An example of an ecosystem service is the role played by insects, especially bees, in the pollination of plants, including staple food crops. There is an industry in many intensively farmed parts of the world in moving hives and their resident honey-bees to orchards and other areas where pollination is needed. Recent declines of bee populations have had considerable economic impact: for example, in Maoxian County of Sichuan, China, the free service of pollination by insects has had to be replaced by the labour-intensive service of human hand pollination. On a much smaller scale, though equally importantly, there are micro-organisms that provide the services of removing waste produced by human society and recycling it or rendering it harmless. Both the bees and the waste-handling organisms, however, are part of a larger system of interdependencies and they themselves rely on their ecosystems for their survival.

These natural services are of enormous value to human society. Costanza et al. (1997) estimated the annual value of these services at $33 trillion, compared with a global gross national product total at that time around $18 trillion per year. Although this figure has proved controversial, there is no doubt that ecosystem services represent a massive contribution to the economic well-being of all societies. Many of the services are simply irreplaceable: for example, we have no way of providing food for the human population except through the use of natural systems involving soil, soil organisms and crop plants, nor of providing drinking water, except through the operation of the water cycle which depends critically on the activities of organisms. The maintenance of ecosystems, therefore, must be an essential part of the survival strategy for human societies. However, there is little evidence that this message has been understood.

In a recent survey, Pearce (2006) attempted to relate actual conservation efforts to economic values (measured through stated preferences or otherwise), and concluded that 'actual expenditures on international ecosystem conservation appear to be remarkably small and bear no relationship to the willingness to pay figures obtained in the various stated preference studies.' Actual expenditures through bilateral assistance, the Global Environmental Facility, debt-for-nature swaps and support for protected areas is probably less than $10 billion per annum, much less than is required efficiently and effectively to protect ecosystems and safeguard the future flow of ecosystem services (see, for example, James et al. 2001; Balmford et al. 2002). Upon comparing various estimates of the costs and benefits of conserving ecosystems, Pearce concluded the data were inadequate to determine the economic value of global conservation efforts, but that the lack of financial backing to conservation agreements suggests that 'despite all the rhetoric, the world does not care too much about biodiversity conservation.'

Great uncertainty is associated with the valuation and management of biodiversity. Nevertheless, the sheer scale of the services provided by ecosystems suggests that the effort put into maintaining their ability to deliver essential services is unlikely to be sufficient. Taken together, these findings suggest that despite conservation efforts, ecosystems are still under threat, so that future flows of ecosystem services will be compromised; this situation is unlikely to be economically efficient, as recognised in the parallel case of societal response to climate change by the Stern report (Stern 2007).

What are the consequences? Because ecosystem services are economically valuable and loss of biodiversity could translate into welfare losses for humans, economists are increasingly interested in the topic. Important though formal economic analyses of ecosystem services may prove to be, it has been argued that ecosystems (or biodiversity) have a value that cannot be expressed in these terms, or that biodiversity has alternative values that should be taken into account when designing policy. Although an economic approach incorporates many relevant values – use and non-use values – some values (for example intrinsic values) lie outside the economic domain. In matters with strong moral repercussions, such as biodiversity conservation, economics does not provide a one-stop shopping framework for decision-making.

However, the power of economic analysis within the policy-making processes in Europe is such that argument is constructed in a major part through the language of costs and benefits. To address the chronic underinvestment in conservation of biodiversity and to ensure that future decisions do not lead to an unacceptable further loss of biodiversity, it is essential that the value of biodiversity in promoting the delivery of essential and valuable services is expressed strongly (in both economic and other terms) in those areas of decision-making where economic analysis is itself strongest.

1.2 The current study

The current study has been commissioned by the Council of the European Academies Science Advisory Council (EASAC) as a contribution to the scientific debate on the future of European biodiversity. EASAC is an independent association of the science academies of the European Member States.

Part of EASAC's role is to highlight issues of European importance and to offer advice on them to the European institutions of governance. Annex 2 contains further background on this study.

Ecosystems represent the intersection of the living and non-living worlds: they are the stage on which organisms interact with the physical world. As such, they provide a range of provisioning, regulating, cultural and supporting services that underpin human well-being. These services imply a real monetary value for the benefits received by society from the ecosystem and real losses from its impoverishment. A focus on the concept of ecosystem services and the benefits they provide to society therefore provides a framework for the identification and assignment of value. We need to understand how these services are delivered: does it matter if an ecosystem on which we depend for the provision of clean water or climate regulation has few or many species? What will be the consequences of losses of species, or of particular species from the ecosystem, particularly in relation to the system's capacity to absorb disturbances? How can management of ecosystems improve so that otherwise inevitable trade-offs among services can be reduced? We need to understand what features of ecosystems enhance the delivery of services and, conversely, what damaging actions can reduce that delivery, not only so that we can manage them appropriately but also to assign more accurate economic values to them in the economic models that typically determine policy.

This report has the following purposes:

1. To assess the scientific consensus around the concept of ecosystem value by bringing together a selection of leading scientists and economists working in this field across Europe to provide an up-to-date scientific review of the concept and how it may be used in economic models.
2. To contribute to the evidence base by providing a scientific overview of knowledge about ecosystem function and services and their interactions with biodiversity with the aim of identifying the main gaps and target areas.
3. To help in the identification of the role of European ecosystems in delivering services and to assist policy-makers in maintaining ecosystem services in Europe.

In discussions of ecosystem services, an assumption is often made that ecosystems with many species are inherently better able to deliver specific services, either immediately or in a sustainable manner. This assumption is likely to be more true for some service elements than others; for example, in the case of carbon storage in the environment, which is a crucial issue in understanding how ecosystem change will affect climate change, deep peat maximises carbon storage and is typically associated with very low biodiversity. In contrast, primary production, which determines the rate at which excess carbon dioxide is removed from the atmosphere, is promoted by increasing biodiversity, in the absence of large and unsustainable inputs of resources by human activity. Loss of biodiversity may therefore have a greater impact on the initial process of sequestration than on long-term stores, leading to marked regional variations in sequestration capacity. Similar contrasts can be identified for other services. In this study, a range of ecosystem services within a European context has been examined in order to draw conclusions about the significance of biodiversity in supporting these.

The report was prepared by an expert Working Group appointed by EASAC Council and Chaired by Professor Alastair Fitter FRS. The Working Group members, from six EASAC member academies, are listed in Annex 3.

1.3 Methods

This EASAC Study has been made in four stages:

1. Prioritisation of ecosystem services within a European context: the group used the systematisation of services developed by Millennium Ecosystem Assessment. The importance of services to the European environment, economy and societies is not equal, and their significance will vary regionally.
2. Assessment of the relative significance of biodiversity for each of these services.
3. Identification of the parts of the ecosystem (for example soil, water) where biodiversity is important in each case and an evaluation of the knowledge base for each.
4. Statement of the consequent threat level to the provision of these services: that is, the extent to which threats to the maintenance of biodiversity in Europe can be identified as a threat to the provision of specific services, both regionally and locally.

Working Group members prepared an initial assessment of these factors, which was extensively reviewed by a wide range of experts, also listed in Annex 3. Comments and contributions from reviewers were taken into account in this report, which was then subject to a review within the member academies before publication.

2 Ecosystem services and biodiversity

2.1 What are ecosystem services?

The ecosystem concept was introduced by the pioneer ecologist Arthur Tansley in 1935, who stated 'we cannot separate [organisms] from their special environment, with which they form one physical system'. An ecosystem then is the interacting system of living and non-living elements in a defined area, which can be of any size, although in most uses ecosystems are large-scale entities. Thus a lake or a forest may be defined as an ecosystem. The importance of the ecosystem is that it is the level in the ecological hierarchy (see Box 1) at which key processes such as carbon, water and nutrient cycling and productivity are determined and can be measured: these are the processes that determine how the world functions and that underlie all the services identified by the United Nations Millennium Ecosystem Assessment.

Ecosystem services are defined by the Millennium Ecosystem Assessment as the benefits people obtain from ecosystems. The four broad categories recognised by the Assessment and which form the framework for this report are:

1. **Supporting services**, which provide the basic infrastructure of life, including the capture of energy from the sun, the formation and maintenance of soils for plant growth, and the cycling of water and nutrients. These services underlie all other categories.

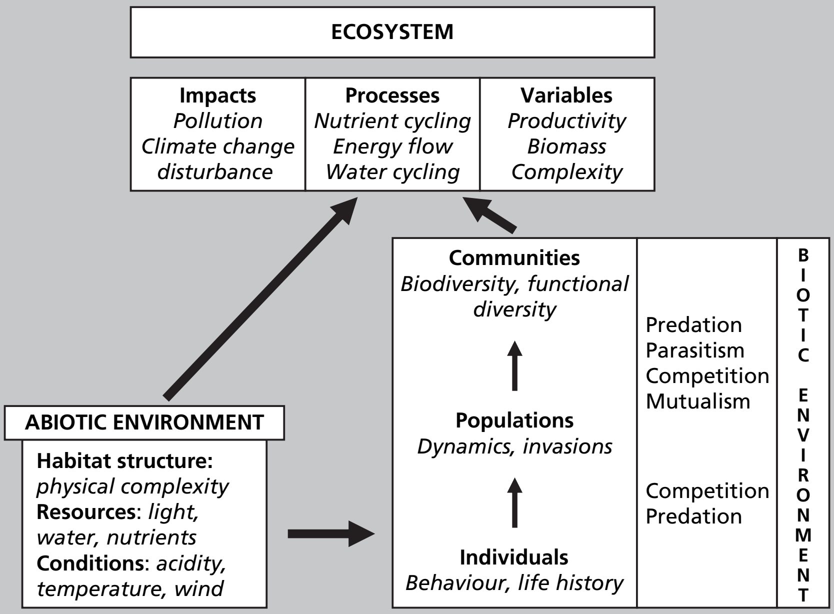
2. **Regulating services**, which maintain an environment conducive to human society, managing the climate, pollution and such natural hazards as disease, flood and fire.

3. **Provisioning services**, the provision of the products on which life depends, food, water, energy, and the materials that human society uses for fashioning its own products.

4. **Cultural services**, the provision of landscapes and organisms that have significance for humankind because of religious or spiritual meanings they contain or simply because people find them attractive.

A detailed analysis of these services is provided in Annex 1.

Box 1 The ecological hierarchy



The diagram represents the components of the ecosystem, which comprises the abiotic factors of the environment and the biological communities that live there. Communities are made up of populations of organisms whose individuals interact with each other and with those in other populations by competing for resources and preying on or parasitising others. It is the individuals that respond to the abiotic factors of the habitat. Processes in ecosystems, which underlie ecosystem services, are the result of the interaction of the organisms and the abiotic environment.

The ecosystem is one stage in a hierarchy of systems recognised by the science of ecology, from the population (the individuals of a single species in a defined area), through the community (the set of populations in that area), to the ecosystem, which brings in the abiotic elements. Although ecologists recognise landscape units such as forests and lakes as ecosystems, they also accept that ecosystems are not self-contained: they have porous boundaries and both organisms and materials move between systems, often with important ecological consequences. Above the ecosystem in this hierarchy, ecologists recognise biomes and the biosphere; both of these are at much larger scale, continental or global.

The Millennium Ecosystem Assessment classification is based on an anthropocentric view of the functioning of ecosystems: it explicitly addresses the benefits that human societies gain. The delivery of these services, however, represents the normal operation of the ecosystem, and reflects the natural processes that occur within every ecosystem. The services, therefore, which are a human construct, depend on these underlying processes, such as:

- fixation of nitrogen gas from the air by bacteria into forms that are useable by plants, which underlies the nitrogen cycle;
- decomposition of organic matter by microbes, which is the basis of all nutrient cycles, including importantly the carbon cycle;
- interactions between organisms, such as competition, predation and parasitism, which control the size of their populations.

Because the processes depend on organisms and the organisms are linked by their interactions, the services themselves are also linked. For example, productivity can only be maintained if the cycling of nutrients continues, and all provisioning services depend intimately on the supporting services of production and water and nutrient cycling. It is essential to understand, therefore, that all ecosystems deliver multiple services, although the relative scale of the various services will vary greatly among ecosystems. This variation in scale is greatly exacerbated when ecosystems are managed by people: typically this management focuses on a single service, be it food production or water cycling, and the consequence of this is nearly always a reduction in delivery of other services.

The most extreme cases of human alteration of ecosystems are found in some forms of intensive agriculture, where the focus of management is to divert all production through a single crop species, and in urban environments, where the soil may be extensively covered with impermeable surfaces such as concrete and tarmac. In both of these cases, the delivery of a wide range of alternative ecosystem services will be minimal.

2.2 What is the relationship between biodiversity and ecosystem services?

All ecosystems contain living organisms, although in some cases there will be few different species or types whereas in others there will be many. This richness of biological types is known as biodiversity, and is seen at its most intense in iconic ecosystems such as coral reefs and tropical rainforests, where the conditions for life are generally favourable. In contrast, ecosystems characterised by extreme environmental factors, either extreme cold, as in the Arctic, or toxins, as on very acid or polluted soils, may have little biodiversity.

The reasons why ecosystems vary so greatly in biodiversity are complex but well studied. Generally, productive natural ecosystems have the highest biodiversity: on a global scale this is apparent in the remarkable gradient of increasing species richness that occurs as one travels from the poles towards the equator. Nevertheless, many highly productive ecosystems, and especially those under human management, have low biodiversity, showing that many other factors are at work. Among those factors are rates of evolution, which are the underlying driver of biodiversity; rates of dispersal, both natural and assisted by humans, which are especially important when ecosystems are isolated from others by natural barriers; and the complex set of interactions between species, such as predation, competition and parasitism, which control the sizes of their populations and often their persistence in a community. Many factors therefore determine how many species occur in an ecosystem and hence its biodiversity; importantly, the biodiversity of an ecosystem is never fixed and will change, often markedly, as the environment changes.

One striking feature of ecosystems with many species is that these species can be grouped into sets that have similar ecological roles, called functional groups. For example, among the plants in a grassland ecosystem, there will be some species, such as legumes, that form a symbiosis with nitrogen-fixing bacteria in their roots and gain access to the pool of atmospheric nitrogen for their nutrition; they form a distinct functional group from the other species. Similarly, some spiders catch prey in webs, others by hunting: these represent distinct functional groups of predators and they play distinct roles in an ecosystem. In a diverse ecosystem there will be many legumes or many wolf spiders; in a species-poor system, there may be only one of each. Even where there are many species within a functional group, some will always be rare and others common. There may be some that play especially important roles in the ecosystem; these are known as keystone species (note, however, that a keystone species may not necessarily be a common species). It is obvious that losing an entire functional group from an ecosystem or the keystone species from within that group is likely to have more severe consequences for its functioning than losing one species from a large group. Nevertheless, experimental evidence shows that both number of species and number of functional groups can play an important role in controlling ecosystem processes (Reich et al. 2004)).

Ecosystems can certainly change drastically when sets of key species are lost (Estes and Duggins 1995; Terborgh et al. 2001) or when new species invade (Vitousek and Walker 1989). One of the great unsolved problems in ecology is to determine how important that biological richness is for the operation of processes such as production and nutrient cycling. Experiments have shown that when there are more species in an ecosystem, and especially more types of species with distinct functional attributes, ecosystem processes such as biomass production, pollination and seed dispersal are promoted. It is less certain what happens to an ecosystem as it progressively loses species, but because processes in ecosystems with very low biodiversity are in many cases slower or less active, it follows that loss of species will eventually cause degradation of processes. Although the shape of the relationship is not entirely clear (do services decline progressively or suddenly as biodiversity is lost?) there is evidence that it is highly non-linear. A slight decreasing trend in ecosystem functions as species diversity declines is often followed beyond a certain threshold with a collapse of function.

Despite the uncertainties surrounding the mechanisms that link biodiversity to ecosystem processes and services, there are numerous well-documented examples that demonstrate that biodiversity plays a large role in many cases. Within the context of the Millennium Ecosystem Assessment framework, such examples would include:

Supporting services: in a meta-analysis of 446 studies of the impact of biodiversity on primary production, 319 of which involved primary producer manipulations or measurements, there was 'clear evidence that biodiversity has positive effects on most ecosystem services', and specifically that there was a clear effect of biodiversity on productivity (Balvanera et al. 2006).

Regulating services: in an experimental study of pollination in pumpkins, it was the diversity of pollinator species and not their abundance that determined seed set (Hoehn et al. 2008).

Provisioning services: where grassland is used for biofuel or other energy crop production, the lower financial return makes intensive production systems involving heavy use of pesticides and fertilisers uneconomic; mixed swards of grasses are more productive under less intensive production systems than pure swards (Bullock et al. 2007).

Cultural services: evidence from the 2001 foot and mouth disease epidemic in the UK demonstrated that the economic value of biodiversity-related tourism greatly exceeds that of agriculture in the uplands of the UK.

2.3 Land use and multiple services

The interaction of organisms and their environment underlies the ecosystem concept. The services that this report addresses arise from the normal functioning of ecosystems, and their delivery is affected as ecosystems are altered by natural events or human exploitation. In many ecosystems, the primary production is increasingly diverted to human use and is not therefore available to other species that may play an important role in regulating the ecosystem, for example by controlling the populations of potential pest species. In more extreme cases, human activity leads to severe degradation of the ecosystem, by gross interference (for example canalisation of rivers) or pollution (for example by heavy metals).

Nevertheless, ecosystems that have been altered by human activity still deliver important services; indeed, the management of the ecosystem may be directed at maximising some particular service, most obviously in agro-ecosystems where food production is the major output. However, all ecosystems deliver more than one service, and therefore manipulation of an ecosystem to maximise one particular service risks reducing others. For example, forests regulate water flow and quality and store nutrients in soil, among many other functions; clear-felling a forest to obtain the ecosystem service of timber products results in the temporary failure of the system to retain life-supporting nutrients in the soil, as shown by the classic Hubbard Brook experiments in New England, USA (Likens et al. 1970) . Similarly, arable land is typically managed to maximise yield of food crops, but one consequence is often a reduction in the amount of carbon stored in soil, with negative effects on the service of climate regulation (Smith 2004).

The most extreme examples of human alteration of ecosystems are found in urban areas where ecosystems typically contribute minimal levels of provisioning services. Urban landscapes are characteristically heterogeneous: parts of an urban landscape may have very few species, whereas elsewhere there may be substantial biodiversity, often due directly to human presence (Elmqvist et al. 2008). Green areas, street trees and urban vegetation may generate services related to environmental quality such as air cleaning, noise reduction and recreation. Such services may be of high value for human well-being in urban regions (Bolund and Hunhammar 1999). Services related more directly to human health could also be substantial: Lovasi et al. (2008) showed that asthma rates among children aged four and five in New York City fell by 25% for every extra 343 trees per square kilometre. Characteristic of many of the urban ecosystem services is that they are often generated on a very small scale: patches of vegetation and even individual trees may generate services of high value.

Urban areas constitute large-scale experiments on the effects of global change on ecosystems where significant warming, increased nitrogen deposition and human domination of ecosystem processes are already prevalent (Carreiro and Tripler 2005). The impact of urban areas extends far beyond their boundaries: although urbanisation consumes only about 4% of the total land area worldwide, its footprint includes the vast areas of land used for intensive food production and all the other provisioning services required to maintain the urban population, as well as the impacts on regulating services brought about, for example, by massive greenhouse gas production and distortion of the hydrological cycle.

Even where human impact is more benign or has less impact, decisions will be needed on prioritisation among services. All ecosystems deliver multiple services: some of these will be complementary and some conflicting. For example, maintenance of soil integrity will promote nutrient cycling and primary production, enhance carbon storage and hence climate regulation, help regulate water flows and water quality, and improve most provisioning services, notably for food, fibre and other chemicals. In contrast, wherever services are delivered by maintaining monocultures of a single species, as is often the case for production of food, fibre and energy, this will reduce the delivery of services more dependent on the maintenance of biodiversity, including pollination and disease regulation.

In managing land (and where appropriate water), people always, even if only implicitly, do so to achieve benefits of ecosystem services, but because these services are not independent of one another, a major challenge is how to manage trade-offs between the services. Different types of trade-off can be identified:

- *Temporal trade-offs*: there may be benefits now with costs incurred later (or more rarely vice versa). Land used for food production may store progressively declining stocks of organic matter, with long-term consequences both for nutrient cycling, and hence future fertility, and carbon sequestration.

- *Spatial trade-offs*: the benefit may be experienced at the site of management, but the cost incurred elsewhere. Moorland, burned to maximise growth of young heather shoots and the number of grouse, and hence the income from grouse shooting, increases the loss of dissolved organic matter to water, which appears as colour in drinking water and has to be removed at great expense by water companies.

- *Beneficiary trade-offs*: the manager may gain benefit, but others lose, leading to actual or potential conflict. Most management systems that maximise production by high inputs of fertilisers lead to reduced biodiversity, so that those who appreciate land for its conservation value lose. Equally, land managed for biodiversity conservation, such as nature reserves, has little production value.

- *Service trade-offs*: these occur almost invariably when management is principally for one service and are in practice similar to beneficiary trade-offs.

These trade-offs are real and well documented. The challenge is to move towards 'win–win' or at least 'win more and lose less' management strategies. This goal can be achieved in several ways:

- by improving access to information on ecosystem services and their valuation;

- by integrating ecosystem services into global, national and local planning;

- by ensuring equity and consistency of rules and their application;

- by framing and using appropriate incentives and/or markets;

- by clarifying and strengthening rights of local people over their resources.

To control the impact of these trade-offs, it will be essential to take into account the spatial and temporal scale at which ecosystem services are delivered. Examples of services that operate at different scales are:

- pollination, which operates at a local scale and can be managed by ensuring that there are areas of land managed that maintain populations of pollinators in a mosaic of land-use types;

- hydrological services which function at a landscape scale, such as a watershed, and which require co-operation among land managers at that scale; and

- carbon sequestration in organic matter in soil, which operates at a regional and global scale and necessitates policy decisions by governments and international bodies to ensure that appropriate incentives are in place to ensure necessary behaviour by local land managers

3 European biodiversity and ecosystem services

3.1 Patterns of European biodiversity

Europe's cultural landscapes have been shaped by traditional land uses. These landscapes provide numerous ecological services. No European ecosystems are unaffected by human activity, either directly (farming, forestry, urbanisation) or indirectly (pollutants, nitrogen deposition, climate change); most European ecosystems are more or less intensively managed.

Within Europe, the distribution of species and ecosystems is widely variable, with the centres of biodiversity occurring in the Mediterranean basin, on the margins of Europe in the Caucasus Mountains (Ukraine, Georgia, Armenia) and in the eastern Alps. Diversity also trends downwards with latitude and is lower in areas severely affected by glaciation within the past 15,000 years, notably in northwest Europe. Islands often have low biodiversity overall both because they are small in area and because of the failure of otherwise widespread species to colonise them after disturbance such as glaciation. Conversely, they frequently have endemic species or races, as a result of evolutionary processes in isolated populations: Ireland, for example, has only 25 species of native mammal and fewer than 1000 native plant species. Within a given climatic zone, biodiversity tends to be greatest in habitats characterised by intermediate levels of disturbance, nutrients and water supply: at both extremes, diversity declines.

The European landscape is dominated by agriculture (44%), forests (33%) and by spreading urban and recreation areas. Many of the forests are managed for timber and are plantations, often of a single or very few exotic tree species. Habitats that were formerly the main reservoirs of biodiversity, such as semi-natural and natural grasslands, heathlands, wetlands and old forests, have been decreasing, with deleterious consequences for European biodiversity as a whole. In contrast, arid lands are increasing, especially in southern Europe.

One of the most detailed studies of recent changes in biodiversity was the *New Atlas* project for flowering plants in Britain and Ireland (Preston et al. 2002). This compared systematic records made in the periods 1930–1969 with those in 1987–1999 and showed that there had been marked increases in distribution of recently introduced species and those found in nutrient-rich habitats, whereas arable weeds, species of nutrient-poor habitats, and species of open ground had all declined. These changes reflect the changes in agricultural practice, increasing loss of undisturbed habitats and the widespread deposition of atmospheric nitrogen in the region.

3.2 An assessment of ecosystem services and biodiversity in Europe

The Millennium Ecosystem Assessment offers a global view of the importance of ecosystem services. To achieve an understanding of the relative significance of different ecosystem services in Europe and the role played by biodiversity in delivering them, as needed by policy-makers in the EU, we have undertaken a poll of expert opinions. Working Group members and other experts were asked to assess each of the Millennium Ecosystem Assessment ecosystem services in this context, to comment on the threats to the services and to suggest urgent research needs. The full assessment of ecosystem services made in the course of this study is given in Annex 1. This section highlights the role that ecosystem services play in Europe the part played by biodiversity in forming and sustaining these services and European level concerns about them.

A Supporting services

These are the basic services that make the production of all the other services possible.

A1 Primary production

Primary production in the Earth's ecosystems is recognised as fundamental to all other ecosystem services and appears to be strongly dependent on biodiversity. It is the best studied of the supporting services. Primary production is generally high in Europe because soils are young and hence fertile, and climate is generally benign. Low productivity is associated with very cold regions (Arctic and alpine), very dry regions (some parts of the Mediterranean region) and seriously polluted or degraded environments.

Although there is a close association between primary production and biodiversity, the mechanisms involved are an important area for further research.

In ecosystems without external nutrient input, biodiversity often enhances production. Environmental pressures, such as changes in land use, climate change and pollution, all reduce both quantity and quality of biodiversity and hence have an impact on productivity (see, for example, Ciais et al. 2005).

Maintaining primary production of agricultural, natural and semi-natural ecosystems is essential for achieving several policy goals, including carbon sequestration in soils and vegetation, agricultural production and use of land for other productive purposes. Achieving good levels of agricultural productivity in biodiverse systems will be important in economic development of rural areas to encourage tourism alongside traditional agricultural livelihoods (see, for example, Bullock et al. 2007).

There are concerns that the increasingly dry conditions in southern Europe will lead to a decline in primary productivity. This may be offset to an extent by increased productivity in the northern parts of Europe as they respond to warming. That local increase of primary productivity from fertilisers used in agriculture and from pollution may come at the cost of ecosystem damage and consequent loss of other services through eutrophication.

A2 Nutrient cycling

Nutrient cycling is also considered a highly important ecosystem service for Europe. It is a key process in both terrestrial and aquatic systems and is essential for maintenance of soil fertility. Nutrients are cycled as organisms grow, taking them up, and then decompose, releasing them back into the environment. Biodiversity is critical to these cycles.

The capacity of ecosystems to sequester nutrients depends, besides natural factors, on management interventions. In intensively farmed landscapes, nitrate and phosphate may be lost to watercourses, causing both damage to water quality and economic losses on farms. Disruption to nutrient cycles can be brought about by atmospheric deposition of nitrogen, sulphur and sometimes metals to soils – through effects including acidification, denitrification, inhibition of fixation – and by sewage, industrial and agricultural effluents in aquatic systems. It is of considerable concern in Europe.

The widespread use of sewage sludge as an agricultural fertiliser, though an effective way of recycling nutrients removed from soils by agriculture, has resulted in contamination of soils by heavy metals (for example zinc, copper, cadmium), which inhibit nitrogen-fixing bacteria. Changes in biodiversity of natural ecosystems brought about by land-use change, climate change or pollution alter the ability of ecosystems to retain nutrient stores, resulting in release of nutrients to other ecosystems with potentially damaging consequences.

Research into the ability of soil organisms to resist anthropogenic pollution is urgent as, despite a considerable volume of European legislation, acid deposition and eutrophication persist in much of the EU environment with the potential for accumulating damage to essential nutrient cycles

A3 Water cycling

Urbanisation, climate change and intensive agriculture have placed Europe's water resources under considerable pressure. The services provided by the environment in distributing, purifying and controlling water are becoming increasingly important. Natural processes play key roles: vegetation is a major factor in controlling flows, and soil micro-organisms are important in purification. However, the role of species diversity is not clear as many of the processes can be performed by a wide variety of species. There appears therefore to be considerable scope for species to substitute for each other and biodiversity plays only a moderate role.

The water cycle is an important process in the overall management of water. Humans have made massive changes in water cycles through drainage, dams, structural changes to rivers and water abstraction. Runoff has become more rapid owing to changes in landscapes, including deforestation, land drainage and urbanisation. Many of those impacts are likely to be amplified through climate change, which will result in different patterns of water movement both spatially and temporally, including a greater frequency of extreme events (storms, droughts, etc.) and long-term trends in precipitation and evaporation. Both vegetation and soil organisms have profound impacts on water movements and the extent of biodiversity is likely to be important. Changes in species composition can affect the balance between water used by plants ('green water') and water flowing through rivers and other channels ('blue water'), and native flora may be more efficient at retaining water than exotic species. A key control on the water cycle is the ease with which water penetrates soil. Where penetration is low because of compaction or development of surface crusts, runoff is increased, which alters the blue:green balance. The main problems in Europe arise in the south because of deficit of water and in some central European areas which are frequently flooded.

A4 Soil formation

Soil formation is a continuous process in all terrestrial ecosystems, but is particularly important and active in the early stages after land surfaces are exposed. It is a highly important ecosystem service in Europe. Soil formation is fundamental to soil fertility, especially where processes leading to soil destruction or degradation (erosion, pollution) are active. Soil biodiversity is a major factor in soil formation. Loss of soil biota may reduce soil formation rate with damaging consequences. Intensive agriculture can also reduce soil quality in other ways, for example by removal of organic residues so that organic carbon incorporation into soil is less than the rate of decomposition, leading to reduced soil carbon, with nutritional and structural consequences for soil. There will be particular concerns on soils that are subject to intense erosion, by wind or water. Northern European ecosystems are still in the early stages of recovery from glaciation and consequently soils are often resilient to intensive agricultural use (Newman 1997). Much of the Mediterranean region, however, has older soils with lower resilience that have suffered severe damage and are often badly eroded (Poesen & Hooke 1997). In alpine areas, high rates of erosion may be countered by high rates of soil development.

There is, then, a contrast between northern Europe whose young soils are relatively resistant to intensive agriculture and the Mediterranean region where there has been considerable damage and erosion. Biodiversity of soil organisms plays a major part in creating soil and maintaining soil function.

B Regulating services

These are benefits obtained from the regulation of ecosystem processes.

B1 Climate regulation

Climate regulation refers to the role of ecosystems in managing levels of climate forcing gases in the atmosphere. Current climate change is largely driven by increases in the concentrations of trace gases in the atmosphere, principally as a result of changes in land use and rapidly rising combustion of fossil fuels. The major greenhouse gas (CO_2) is absorbed directly by water and indirectly by vegetation, leading to storage in biomass and in soils, ensuring the regulation of climate. Other greenhouse gases, notably methane (CH_4) and nitrous oxide (N_2O) are also regulated by soil microbes. The interplay between biodiversity and climate regulation is poorly understood. The global carbon cycle is strongly buffered, in that much of the CO_2 discharged by human activities into the atmosphere is absorbed by oceans and terrestrial ecosystems (Janzen 2004).

Globally and on a European scale, climate regulation is one of the most important ecosystem services. European ecosystems play a major role; it has been calculated (see Annex 1 B1) that Europe's terrestrial ecosystems represent a net carbon sink of some 7–12% of the 1995 anthropogenic emissions of carbon. Peat soils contain the largest single store of carbon, and Europe has large areas in its boreal and cool temperate zones.

The problem we face is that the rate of emissions exceeds the capacity in oceans and terrestrial ecosystems for buffering, and the loss or damage to ecosystem function through the indirect effects of human activities is reducing this capacity still further. Strategies will have to be adjusted to manage areas with high carbon sequestering potential. The most promising measures include: higher organic matter inputs on arable land, the introduction of perennials (grasses, trees) on arable set-aside land for conservation or biofuel purposes, the expansion of organic or low-input farming systems, raising of water tables in farmed peatland, and the introduction of zero or conservation tillage. In Europe there are strong regional variations in trace gas emissions and absorption. These suggest that soils across Europe vary in the contribution they make to climate regulation services. For instance, peat soils have especially high carbon contents, and Europe contains extensive areas of peat containing large quantities of carbon. Biodiversity of low-input ecosystems facilitates primary production and thus carbon sequestration.

Given the importance of carbon storage, it is essential that the key ecosystems, in particular the peat soils, continue to function well. Knowledge about their performance and the mechanisms that underlie carbon sequestration and storage is therefore crucial. However, research is needed on the contribution of biodiversity to climate regulation, a significant problem given that soil biodiversity is under threat from many soil management practices. The current evidence suggests that biodiversity has a moderate impact in climate regulation.

B2 Disease and pest regulation

Pests and diseases are regulated in ecosystems through the actions of predators and parasites as well as by the defence mechanisms of their prey. The services of regulation are expected to be more in demand in future as climate change brings new pests and increases susceptibility of species to parasites and predators.

Disease regulation is therefore related to the control of the prevalence of pests and diseases of crops and livestock, but also of human disease vectors and disease. Major outbreaks of both human and wildlife (animal and plant) diseases are usually caused by the introduction of a new pathogen. Management of diseases can involve several approaches: control of diseased hosts, replacement of susceptible by resistant hosts; ecosystem management to reduce spread of the disease organism; biological control of pathogens; and chemical control of pathogens. Some ecosystems may be better able to resist invasion by novel pathogens than others, possibly because of factors such as the structure and complexity of ecosystem.

The role of biodiversity in disease regulation may be important. There is evidence that the spread of pathogens is less rapid in more biodiverse ecosystems. There is also a consensus that a diverse soil community will help prevent loss of crops due to soil-borne pests and diseases (Wall and Virginia 2000). Higher trophic levels in soil communities can play a role in suppressing plant parasites and affecting nutrient dynamics by modifying abundance of intermediate consumers (Sanchez-Moreno and Ferris 2006). In many managed systems, control of plant pests can be provided by generalist and specialist predators and parasitoids (Zhang et al. 2007; Naylor and Ehrlich 1997). There is a need for the development of European applications of biological control, exploiting the properties of pest regulation in biodiverse ecosystems.

B3 + C2 Water regulation and purification

The water regulation and purification service refers to the maintenance of water quality, including the management of impurities and organic waste and the direct supply of clean water for human and animal consumption. Soil state and vegetation both act as key regulators of the water flow and storage. Changing land use (forest cover, use of drainage) is a major factor, as is changing climate – with consequent high-intensity rainfall events and more seasonality in rainfall distribution. Although vegetation is a major determinant of water flows and quality, and micro-organisms play an important role in the quality of groundwater, the relationship of water regulation and purification to biodiversity is poorly understood. In lowland Europe, there are several factors that impinge on water regulation and purification, including use of floodplains, river engineering and increasing urbanisation leading to higher levels of run-off and contamination of water. Increasing land-use intensity and replacement of biodiverse natural and semi-natural ecosystems by intensively managed lands and urban areas have resulted in increased runoff rates, especially in mountainous regions. Increasingly, freshwater supplies are a problem in the Mediterranean region and in such densely populated areas as southeast England. A more coherent approach to the managed recharge of groundwater, with controls on groundwater extraction rates to protect surface ecosystems would be a valuable enhancement to the Water Framework Directive.

B4 Protection from hazards

This is a regulating service reducing of the impacts of natural forces on human settlements and the managed environment. It is highly valued in Europe. Many hazards arising from human interaction with the natural environment in Europe are sensitive to environmental change, including flash floods due to extreme rainfall events on heavily managed ecosystems that cannot retain rainwater; landslides and avalanches on deforested slopes; storm surges due to sea-level rise and the increasing use of hard coastal margins; air pollution due to intensive use of fossil fuels combined with extreme summer temperatures; fires caused by prolonged drought, with or without human intervention.

Ecosystem integrity is important in providing protection from these hazards, but less so to geological hazards, localised to a few vulnerable areas, such as volcanic eruptions and earthquakes. In alpine regions, vegetation diversity is related to ability to reduce the risk of avalanches (Quetier et al. 2007). Soil biodiversity may play a role in flood and erosion control through affecting the surface roughness and porosity (Lavelle et al. 2006), and increasing tree diversity is believed to enhance the protection value against rockfall (see, for example, Dorren et al. 2004). Increased urbanisation and more intensive use of land for production may reduce the ability of ecosystems to mitigate extreme events.

Biodiversity, then, seems to play a relatively small part, although vegetation itself is very important, for example in preventing avalanches in mountain areas or protecting low-lying coastlines. The existence of a healthy soil community may control infiltration rate of water after heavy rain, modifying storm flows. There will therefore be an indirect impact of biodiversity even in this case.

Environmental quality regulation

Environmental quality regulation is a new category, not in the Millennium Ecosystem Assessment. In addition to services like water purification mentioned above, ecosystems contribute to several environmental regulation services of importance for human well-being and health. Examples include the role of vegetation and green areas in urban landscapes for air cleaning, where parks may reduce air pollution by up to 85% and significantly contribute to reduction of noise. For cities, particularly in southern Europe around the Mediterranean, vegetation and green areas may play a very important role in mitigating the urban heat island effect, a considerable health issue in view of projected climate change. Urban development in Europe, just as elsewhere in the world, faces considerable challenges where efforts to reach some environmental goals, for example increased transport and energy efficiency through increased infilling of open space with urban infrastructure, is not done through sacrificing all other environmental qualities linked to those spaces.

B5 Pollination services

The pollination service provided by ecosystems is the use of natural pollinators to ensure that crops are pollinated. The role of pollinators, such as bees, in maintaining crop production is well documented and of high importance, in Europe as elsewhere in the world. There is strong evidence that loss of pollinators reduces crop yield and that the availability of a diverse pool of pollinators tends to lead to greater yields.

Habitat destruction and deterioration, with increased use of pesticides, has decreased abundance and diversity of many insect pollinators, leading to crop loss with severe economic consequences. The pressures on pollinators may result, apart from decreased crop production, in reduced fecundity of plants, including rare and endangered wild species. Reduction of landscape diversity and increase of land-use intensity may lead to a reduction of pollination service in agricultural landscapes (Tscharntke et al. 2005; Öckinger & Smith 2007). In particular, the loss of natural and semi-natural habitat can impact upon agricultural crop production through reduced pollination services provided by native insects such as bees (Ricketts et al. 2008). There is increasing evidence that diversity of pollinators, not just abundance, may influence the quality of pollination service (Hoehn et al. 2008). Maintenance of biodiverse landscapes, as well as protecting pollinators by reducing the level of the use of agrichemicals (including pesticides) is an important means for sustaining pollinator service in Europe.

The concern at a European level is that change in land use, in particular urbanisation and intensive agriculture, has decreased pollination services through the loss of pollinator species. However, we do not fully understand the causes behind recent declines in pollinators.

C Provisioning Services

These are the benefits obtained from the supply of food and other resources from ecosystems.

C1 Provision of food

Among provisioning services, the delivery and maintenance of the food chain on which human societies depend is of great importance. Heywood (1999) estimates that well over 6000 species of plants are known to have been cultivated at some time or another, but about 30 crop species provide 95% of the world's food energy (Williams and Haq 2002). Intensive agriculture, as currently practised in Europe, is centred around crop monoculture, with minimisation of associated species. These systems offer high yields of single products, but depend on high rates of use of fertilisers and pesticides, raising questions about sustainability, both economically and environmentally. The world may therefore be over-dependent on a few plant species: introducing a broader range of species into agriculture might contribute significantly to improved health and nutrition, livelihoods, household food security and ecological sustainability (Jaenicke and Höschle-Zeledon 2006). Maintenance of high productivity over time in monocultures almost invariably requires heavy subsidies of chemicals, energy and capital, and these are unlikely to be sustainable in the face of disturbance, disease, soil erosion, overuse of natural capital (for example water) and trade-offs with other ecosystem services (Hooper et al. 2005). Diversity may become increasingly important as a management goal, from economic and ecological perspectives, for providing a broader array of ecosystem services.

C2 Water regulation and purification

See paragraph B3.

C3 Energy resources

Energy – the supply of plants for fuels – represents an important provisioning service as well. There is currently strong policy direction to increase the proportion of energy derived from renewable sources, of which biological materials are a major part. At present, this is being achieved partly by the cultivation of biomass crops, which are burned as fuels in conventional power stations, and partly by diversion of materials otherwise useable as food for people. The expectation is that these 'first generation' fuels will be displaced – at least for ethanol production – by a second generation of non-food materials. All of these biofuel production systems present serious sustainability issues. There are already established damaging impacts on food production, availability and prices worldwide. In addition, full analyses of the carbon fluxes show that the carbon mitigation benefits are much smaller than anticipated because of losses of carbon from newly cultivated soils; destruction of vegetation when new land is brought under the plough; losses of other greenhouse gases such as nitrous oxide from nitrogen-fertilised biofuel production systems; and transport and manufacturing emissions. Biodiversity of the crop will probably play a small direct role in most biofuel production systems, although all land-based biofuel production will rely on the supporting and regulating services, for which biodiversity is important. Land-based biofuel production systems have the potential to be especially damaging to conservation of biodiversity because their introduction on a large scale will inevitably lead both to more intensive land use and to the conversion of currently uncultivated land to production. There is, however, the potential of economic incentives for that currently degraded land with little generation of any services being restored to produce biofuel. With the correct regulations and institutions, these areas could simultaneously generate a suite of other services as well.

C4 Provision of fibres

The provision of fibre has historically been a highly important ecosystem service to Europe. Most textiles consumed in the EU are now produced and manufactured abroad. However, the pulp and paper industry has a significant presence in Europe, representing the dominating production of plant fibres in Europe, with most raw pulp being produced from highly managed monocultures of fast-growing pine and eucalypts. Trees planted for pulp are grown at high densities with limited scope for biodiversity. Such large-scale monocultures are vulnerable to runaway pathogen attack (Mock et al. 2007). Biodiverse cropping systems may prove of value for ensuring robust future productivity. Wool production is generally a low-intensity activity on semi-managed pasture lands with the potential to support considerable biodiversity.

C5 Biochemical resources

Ecosystems provide biochemicals – materials derived from nature as feedstocks in transformation to medicines – but also other chemicals of high value such as metabolites, pharmaceuticals, nutraceuticals, crop protection chemicals, cosmetics and other natural products for industrial use. A report from the US

Environmental Protection Agency (2007) concludes that economically competitive products (compared with oil-derived products) are within reach, such as for celluloses, proteins, polylactides, plant oil-based plastics and polyhydroxyalkanoates. The high-value products may make use of biomass economically viable, which could become a significant land-use issue. Biodiversity is the fundamental resource for bioprospecting (Beattie et al. 2005) but it is rarely possible to predict which species or ecosystem will become an important source. Harvesting for biochemicals, however, might itself have a negative impact on biodiversity if over-harvesting removes a high proportion of the species.

C6 Genetic resources

Genetic resource provision, for example provision of genes and genetic material for animal and plant breeding and for biotechnology, is a function of the current level of biodiversity. EU extinction rates remain low; however, there may be problems in poorly studied systems (for example soils, marine environments). Genebanks are better developed in the EU than elsewhere but have limited capacity to conserve the range of genetic diversity within populations. There are now numerous initiatives to collect, conserve, study and manage genetic resources *in situ* (for example growing crops) and *ex situ* (for example seed and DNA banks) worldwide, including most EU countries. New techniques, using molecular markers, are providing new precision in characterising biodiversity (Fears 2007).

Of these provision services, then, only that for food appears to be critical for Europe. The availability of alternative sources from outside Europe, where there is greater general diversity and higher productivity, makes provisioning of fibre, fuel, biochemicals and genetic material from European sources, though important, less critical. Nevertheless, relying on imported materials for many of these provisions may not be sustainable, either economically or environmentally. Biodiversity appears to be a critically important factor in biochemicals and genetic resources. Otherwise the role of biodiversity is less here than in other services.

D Cultural services

These are best considered as falling into two main groups:

(1) spiritual, religious, aesthetic, inspirational and sense of place;

(2) recreation, ecotourism, cultural heritage and educational.

All the services within these groups have a large element of non-use value, especially those in the first group to which economic value is hard to apply. Those in the second group are more amenable to traditional valuation approaches. Biodiversity plays an important role in fostering a sense of place in all European societies and thus may have considerable intrinsic cultural value.

Evidence for the importance of these services to citizens of the EU can be found in the scale of membership of conservation-oriented organisations. In the UK, for example, the Royal Society for the Protection of Birds has a membership of over one million and an annual income of over £50 million. Cultural services based on biodiversity are most strongly associated with less intensively managed areas, where semi-natural biotopes dominate. These large areas may provide both tranquil environments and a sense of wilderness. Low-input agricultural systems are also likely to support cultural services, with many local traditions based on the management of land and its associated biological resources. Policy (including agricultural and forestry policies) needs to be aimed at developing sustainable land-use practices across the EU, to deliver cultural, provisioning and regulatory services effectively and with minimal cost. Maintenance of diverse ecosystems for cultural reasons can allow provision of a wide range of other services without economic intervention.

In Europe, then, cultural services are considered to be of critical importance because of the high value many of Europe's people place on the existence and opportunity to enjoy landscapes and open spaces with their flora and fauna. Although the intrinsic biodiversity of natural space in Europe varies greatly, there is evidence that people value 'pristine' environments and regard the impoverishment of landscape, flora and fauna as negative factors, impacting heavily on their enjoyment of nature. The economic value of ecosystems for tourism and recreation often exceeds their value for provisioning services.

3.3 The significance of ecosystem services in a European context

Table 1 shows the results of the assessment of importance of each particular service relative to its overall global importance. For example, the supporting service of water purification in ecosystems has a high importance for Europe, because of the heavy pressure on water from a relatively densely populated region, whereas the provisioning service of genetic resources is of low importance compared with its overall global importance because there is so much more genetic resource in other parts of the world.

3.4 The role of European biodiversity in maintaining ecosystem services

Information on the role of biodiversity in the continuing flow of these services, though incomplete, suggests that there are ecosystem services of high value in Europe that critically depend on biodiversity. Table 2 summarises the

Table 1 Expert opinion of the importance to the EU of the Millennium Ecosystem Assessment ecosystem services

In this analysis, we have added a new service of environmental quality in the Provisioning category, and we have combined water provision and regulation into a single regulating service.

Category	**Type (Millennium Ecosystem Assessment)**	**EU rating**
Supporting	Soil formation	Locally high: soil formation is most valuable where loss rates of soil by erosion are high or where soils are very young (hundreds of years) and have not yet matured to the point where they can sustain high productivity. This service is therefore most important in mountain areas.
	Nutrient cycling	High: the cycling of nutrients in soils and waters is essential for the maintenance of productivity and has a high value throughout.
	Primary production	High: production underlies all biological processes.
	Water cycling	Locally high: critically important in arid regions of southern Europe.
Regulating	Climate regulation	Locally high: northern European peat soils have global significance as carbon stores.
	Disease regulation	Uncertain: emerging diseases of increasing importance but role played by ecosystems in regulating these is unclear.
	Water	High: the regulating and provisioning services for water are combined here. Flooding and drought becoming increasingly important as rainfall patterns and land-use change; availability of clean water especially significant in heavily urbanised and industrialised areas.
	Pollination	Medium: hard to replace in both natural and agricultural ecosystems.
Provisioning	Food	High: food production a key service in the EU and likely to become more so as global food prices rise.
	Fresh water	Covered under regulating services.
	Fuel	Medium: traditional uses (fuel wood) only locally significant in EU, but rapidly growing emphasis on biofuels may lead this to be a major service.
	Fibre	Medium: important industry in boreal regions; likely to increase in significance in other areas.
	Biochemicals	Low: currently of marginal importance, but could gain significance within novel agricultural systems, providing added value to biomass crops for fuel.
	Genetic resources	Low: current valuation low, but likely to increase.
	Environmental quality	High: provision of goods such as clean air and a safe and peaceful environment already valued, for example in property values.
Cultural	Spiritual/religious/aesthetic/inspirational/sense of place	Values of high importance to many EU citizens but very hard to quantify economic value (see section 4.3); however, extensive membership of wildlife and conservation bodies indicates significance.
	Recreation/ecotourism/cultural/heritage/educational	High: increasingly these are major economic values in rural areas, especially where agricultural value has declined.

Table 2 Expert opinion of the role of biodiversity in maintaining current ecosystem services in Europe

	Increasing role of biodiversity →	
Increasing importance of ecosystem service →	A3: Water cycling A4: Soil formation B1: Climate regulation B3/C2: Water regulation and provision B4: Protection from hazard C1: Food provision C7: Environmental quality	A1: Primary production A2: Nutrient cycling B5: Pollination D2: Cultural services: recreation
	C3: Energy provision C4: Fibre production D1: Cultural services: spiritual	B2: Disease regulation C5: Biochemicals provision C6: Genetic resources

review of expert opinion on this factor. In this part of the review, Working Group members and other reviewers rated each of the Millennium Ecosystem Assessment ecosystem services according to their importance in a European context and the importance of biodiversity in their maintenance (low, medium or high). These ratings form the basis of the assessment in Table 2. The ecosystem services that are of critical importance in Europe (high European importance) have been separated into the upper quadrants, and those for which biodiversity is especially important have been identified and placed in the top right-hand quadrant. The lower quadrants contain those ecosystem services and biodiversity contributions rated medium and low. In Europe it seems that most of the supporting services, including primary production, nutrient cycling and soil formation, are crucially important and depend critically on biodiversity. Pollination stands out as a crucial regulation service depending critically on biodiversity whereas hazard protection, although critical in Europe, depends less on biodiversity.

4 Managing ecosystem services in Europe

4.1 How ecosystems respond to change

All ecosystems experience environmental change and disturbance, varying in scale and impact. Long-term records of ecological history obtained from peats and lake sediments show that change is a normal feature of ecosystems, but also that they have the ability to maintain themselves in the face of change. In the extensive literature on the phenomenon of ecological succession, the successive appearance of distinct communities of plants and animals on a site after disturbance, there is a distinction between primary and secondary succession. Primary succession occurs on bare or recently uncovered surfaces such as muds, glacial moraines and river gravels. Secondary succession is the replacement of an existing community after removal of all or part of the vegetation. The major difference between the two processes is that soil has to be formed in primary succession and the process may take thousands of years, although the early stages can be quite rapid. Secondary succession is often exemplified by the return of woodland to abandoned agricultural fields, a process of substantial interest now that this is a policy objective in many parts of Europe; the same process occurs in miniature in a forest every time a tree dies. A critical control on the rate of community recovery in secondary succession is the ability of the species to survive or disperse back into the disturbed area. If the disturbance is on a very large scale, recovery of the ecosystem can be slow.

The concept of succession implies that communities recover in predictable ways after disturbance. However, sometimes the species previously found on a site fail to re-colonise, for a variety of reasons. If the disturbance is on a very large scale, in space or time, the species may have gone extinct in the area and cannot disperse back in; sometimes, where species are very long-lived such as trees, the local environment may have changed so much that they are no longer able to reproduce or grow from seed. Environmental changes that can bring about such a shift in tolerance include those of the physical environment, such as climate change, and of the biotic environment, such as an invasive species or a parasite. If the environmental change is sufficiently severe, it may shift the community to a new stable state, as happened in the well-documented example of the Newfoundland cod fishery, where the serious disturbance of gross and sustained over-fishing drove the population below a level from which it has been unable to recover.

Sustaining desirable states of an ecosystem in the face of multiple or repeated perturbations therefore requires that functional groups of species remain available (Lundberg and Moberg 2003). Consequently, high levels of biodiversity in an ecosystem can be viewed as an insurance against major disturbance and the likelihood that the community will fail to recover to its original state, simply by increasing the chance that key species will survive or be present. This insurance aspect of biodiversity has been discussed principally in the context of productivity and in simple equilibrium systems (see, for example, Tilman and Downing 1994; Ives and Hughes 2002; Loreau *et al*.2002). However, the insurance metaphor can help us understand how to sustain ecosystem capacity to cope with and adapt to change, even in more complex ecosystems that have numerous possible stable states and in human-dominated environments (Folke *et al*. 1996; Norberg *et al*. 2001; Luck *et al*. 2003). In biodiverse ecosystems, species within functional groups will show a variety of responses to environmental change, and this diversity of response may be critical to ecosystem resilience. However, high species diversity does not necessarily entail high ecosystem resilience or vice versa, and species-rich areas may also be highly vulnerable to environmental change.

The large challenge that remains for ecology is to predict the likely changes in ecosystems after disturbance or environmental change. One approach is to build models based on large-scale ecological patterns, such as the relationship between the number of species and the area being studied, or among the relative abundances of common and rare species in a community. It may then be possible to determine whether fragmentation of habitats, or reduced supply of energy and matter, result in predictable changes on whole ecosystems as a function of their size, and whether losses of ecosystem services are therefore predictable from the way in which an ecosystem responds to change (Southwood et al. 2006).

Predicting ecosystem response to environmental change requires modelling. Schröter *et al*. (2005) used a range of models and situations of climate and land-use change to conduct a Europe-wide assessment of the likely impact of global change on the supply of ecosystem services. Large changes in climate and land use were predicted to result in large changes in the supply of ecosystem services. Although some of these trends may be thought of as positive (increases in forest area and productivity) or offer opportunities (surplus land for agricultural extensification), many induced changes have increased vulnerability as a result of a decreasing supply of ecosystem services (declining soil fertility and green water, increasing risk of forest fires). Mediterranean and mountain regions proved particularly vulnerable.

Modelling tools allow improved regional estimates, and are an increasingly reliable source for estimates of ecosystem response to environmental change. As a significant example of an estimate of European ecosystem response, climate change combined with the effects of increased atmospheric CO_2 concentrations on vegetation growth were shown to produce changes in the cycling of carbon in terrestrial ecosystems (Morales et al. 2007). Impacts were predicted to vary across Europe, showing that regional-scale studies are needed.

There are good prospects for reliably modelling ecosystem responses to environmental change at local or regional scales. Current strategies of habitat management and land use in Europe will need to take into account the vulnerability of ecosystems to environmental change. If we are to ensure the delivery of multiple ecosystem services, ecosystem management strategies need be based on effective monitoring of environmental change and trends in biodiversity.

4.2 Threats to biodiversity, and consequences for ecosystem services in the European Union

The landscapes of Europe have altered substantially in the past 60 years, under the twin pressures of the intensification of agriculture and urbanisation. Many traditional land-use systems have been lost or diminished, as land uses have polarised either towards extensification and even re-wilding on the one hand, or intensification on the other (Pleininger et al. 2006). Some of these pressures have been simply economic, but there has also been a large policy element, especially in agriculture, where price support has driven farm practices. There has been a general lack of coherence of policies; for example, set-aside was designed to address economic issues of farming support but was not optimised to address biodiversity issues, despite its obvious potential to do so.

Intensive agriculture threatens delivery of many ecosystem services, especially in intensively used agricultural areas in European lowlands (for example the Netherlands, parts of southern England and northern France) and in large-scale irrigation systems (for example in Greece). The amount of carbon stored as soil organic matter has declined in most intensive arable soils; improved management practices that take carbon sequestration as a goal could double the amount stored, with demonstrable impacts on carbon emission targets. Many other examples have been documented, including threats to pollinators leading to a decline in the service of pollination, essential for many crops and for all natural ecosystems; increased pest problems due to the more rapid spread of pathogens through ecosystems with low biodiversity; and the impact of atmospheric nitrogen deposition (derived from fossil fuels and excessive use of fertilisers and other intensive agricultural practices) on semi-natural ecosystems resulting in declines in biodiversity and poorer water quality. The evidence for the effects of nitrogen deposition is clear: the long-running (more than 150 years) Park Grass experiment at Rothamsted Experimental Station (now known as Rothamsted Research) in Hertfordshire, UK, shows that a species-rich grassland can be converted to a monoculture of a single grass by sustained addition of high levels of ammonium nitrogen; and the almost complete loss of heathland from the Netherlands has been ascribed to atmospheric nitrogen deposition.

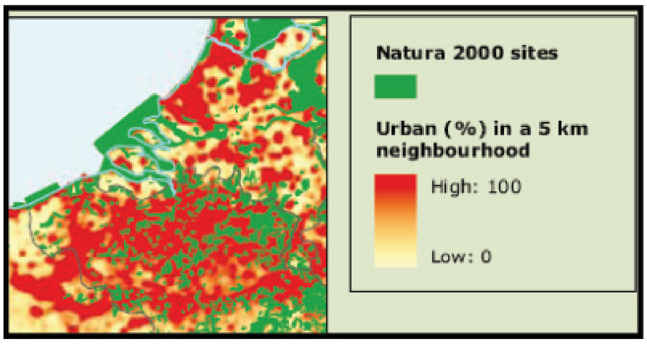
The direct outcome of these pressures on biodiversity is seen in the impact on farmland species. Preliminary indicators based on birds, butterflies and plants suggest a decline of species populations in nearly all habitats in Europe. The largest declines are observed in farmlands, where species populations declined by an average of 23% between 1970 and 2000 (de Heer et al. 2005). Large declines in agricultural landscapes of populations of pollinating insects, such as bees and butterflies, and birds, which disperse seeds and control pests, may have consequences not only on agricultural production but also on maintaining species diversity in natural and semi-natural habitats across Europe.

Landscapes in Europe have also changed through urbanisation. In some regions, such as central Belgium, the effect is to produce a dichotomy between highly urbanised and protected areas (Figure 1). Urban environments have many distinctive features, the most prominent of which is their extreme heterogeneity: there are patches where ecosystem service delivery is minimal, for example where land surfaces are covered with concrete or tarmac, and others where biodiversity may be very high, as in some gardens and parks. A consequence of this heterogeneity is the fragmentation of habitats, which favours species that are effective dispersers but militates against others. This pronounced selection leads to distinctive communities, often dominated by alien species, which by definition are good at dispersing or being dispersed.

4.3 Methods of valuing biodiversity and ecosystem services

Many of these threats to ecosystem services arise because of the way in which different land uses are

Figure 1 Central Belgium is composed principally of highly urbanised areas and areas of high conservation value (Natura 2000 areas). Source: European Environment Agency based on Corine land cover 2000 and Natura 2000.



valued. The immediate value taken into account in decisions is typically expressed in terms of the market price of the land to a developer or the value of a crop it will produce. These approaches ignore the value of the ecosystem services provided by the land, which will be placed in jeopardy by the proposed development. The valuation of ecosystem services offers the potential to place a value on the services forfeited by the development to balance the value of the development itself in assessments of costs and benefits of alternatives. Approaches of this kind have been used widely in project evaluation both of alternative land use and for conservation investments.

The EU has taken as active role in advancing valuations through the recent TEEB (The Economics of Ecosystem Services and Biodiversity) initiative. The report of the first phase of the work (European Communities 2008) highlights the importance of valuation of ecosystems services and the biodiversity that underpins them, and gives powerful global examples. It concludes that there are major threats to ecosystem services from the current high rate of loss of biodiversity but that there is an emerging range of policy instruments, based on valuing ecosystems services, that provides options for managing them in future.

At the most basic level, the services provided by an ecosystem at risk can form a powerful part of the narrative in project assessment. Simply by setting down the nature of the services and their potential scale it is possible to alter the terms of assessment so that the 'development gain' is not the only factor for consideration. In more ambitious assessments, it has proved possible to attach an actual economic value to the ecosystem services or to provide a ranking of alternatives to guide decisions.

4.3.1 Quantitative methods

In recent years there has been considerable progress in attaching monetary value to ecosystem services and, in certain cases, to the biodiversity underpinning them. Ecosystems have value in terms of their use, for example for the production of food or management of flood risk. However, they also have a set of non-use values associated, for example, with the cultural and aesthetic significance they have. It has proved possible to capture both main kinds of value through a range of instruments.

The instruments fall broadly into three main classes, as follows.

1. *Revealed preference methods* based on evidence of current values as shown, for example, in the market price of products, the impact of services on productivity or the costs associated with recreational use of landscape.
2. *Cost-based methods* based on costs such as those of replacing an ecosystem service with other means (hard flood defence as a substitute for coastal wetlands, for example) or of damage costs avoided (the costs of repair to property exposed to erosion by loss of soil function, for example).
3. *Stated preference methods* that assess the amount people say they would be prepared to pay for ecosystem services, once these are fully explained.

Each method has strengths and weaknesses but stated preference methods, especially in the form of contingent valuation, have been most widely used in dealing with the real case of multiple services from an ecosystem. This bias reflects both an ability to handle multiple services better than the more objective methods that tend to focus on single attributes (for example food production or flood defence) and the poor availability of the economic data that those methods require.

Contingent valuation has proved flexible and is both widely accepted and widely researched. It has produced credible results, reflecting real public/community opinions about willingness to pay. Although there remain challenges and it has proved difficult to persuade some policy-makers of the results, contingent valuation remains the most effective means at present of attributing monetary values to complex ecosystems delivering multiple services.

Despite the simplicity and effectiveness of contingent valuation, there is much current interest in the development of markets for ecosystem services, as exemplified by carbon trading schemes. A new tool that is being actively developed is payment for ecosystem services (PES). Wunder (2005) defines a payment for an ecosystem service as a voluntary transaction where a well-defined ecosystem service is bought by at least one buyer from at least one supplier, but only if the supplier secures the provision of the service. The transaction should be voluntary and the payment should be conditional on the service being delivered. Paying for an ecosystem service is not necessarily the same as trading nature on a market: markets may play a role, but because many ecosystem services are public goods, we cannot rely on markets alone. Actions by governments and intergovernmental organisations are also needed.

The way in which PES operates depends on the numbers that benefit from the service and the scale of activity. We can distinguish cases where the ecosystem service benefits a small group of agents from those where it benefits a large and presumably more diverse group. If we consider regulatory services that impact everybody, the ecosystem service resembles a public good. Another useful distinction is between cases where service 'suppliers' and 'demanders' are geographically located close together, so the feedback is local, and those cases where they are not (see Table 3)

There are numerous challenges to the implementation of PES. First, we often have a poor understanding of the 'production function' of ecosystem services and cannot easily estimate how a given management intervention will translate into service outputs, even if we can value those outputs. Second, even successful PES schemes may lead to their own demise because they trigger behavioural changes: for example, paying money to farmers for not growing crops may result in higher prices of food crops, which in turn induce other farmers to convert new areas of habitat into agricultural fields. Third, it is not always obvious who will pay for the ecosystem services, because markets fail in the presence of public goods. Within a nation's borders, government can play an important role: using taxes to pay for public goods is an excellent solution, and the government purchases the ecosystem service from the supplier on behalf of society at large. However, we lack international institutions to broker deals between suppliers of ecosystem services and the rest of the world, though some non-governmental organisations play that role for specific projects and the Global Environmental Facility (GEF), funded by all countries, is designed to deal with global conservation issues.

4.3.2 Qualitative methods: multi-criteria analysis

Generally, economic valuation of biodiversity offers ways to compare tangible benefits and costs associated with ecosystems (Pagiola et al. 2004), but ignores information about non-economic criteria (for example cultural values) that define biodiversity values. However, decision-making processes require knowledge of all influencing factors (OECD 2004). Multi-criteria analysis is a structured approach for ranking alternative options that allow the attainment of defined objectives or the implementation of policy goals. A wide range of qualitative impact categories and criteria are measured according to quantitative analysis, namely scoring, ranking and weighting. The outcomes of both monetary and non-monetary objectives are compared and ranked. Hence multi-criteria analysis facilitates the decision-making process while offering a reasonable strategy selection in terms of critical criteria.

The basis of all valuation methods, however, is an assessment of the nature and scale of the ecosystem services themselves and, in cases where the viability of

Table 3 Classification of cases relevant for payment for ecosystem services

	Local feedback	**International feedback**
Few demanders	Pollination services: loss of insects means that crops may fail and hand-pollination may be required (cf. section 1.1). In Costa Rica's coffee plantations, this service may be worth about $60,000 per farm. Coffee plots close to forests have 20% higher yields thanks to more visiting insects. Farmers might therefore wish to pay the forest owner to offset any incentives that exist to destroy the forest. Hand pollination of fruit trees is now necessary in Maoxian County in Sichuan, China (cf. section 1.1), imposing costs on local farmers.	The Panama Canal and regulatory services: after deforestation, sediments and nutrients flowing into the canal caused clogging and eutrophication, necessitating regular and costly interventions like dredging, while water flows became more episodic. Reforesting the watershed was the cheapest way to maintain the canal. Large companies that depend on the canal were willing to invest in it by underwriting bonds to finance replanting of the forest with native tree species; the companies then qualified for reduced insurance premiums. Here, economics and conservation interests coincide: a profitable business deal yields large environmental benefits.
Many demanders (public good)	Watershed management: a simple market solution cannot apply where the service is a public good and susceptible to free-riders exploiting it: if nobody can be excluded from enjoying a service, it cannot be priced on a market and no-one will invest to make it available. Such market failure does not invalidate PES but does require an institution that enables co-ordination. New York City gets most of its drinking water from the Catskill Mountains watershed. Poor water quality in the 1980s implied large costs for installing water purification plants ($5 billion up-front and $250 million per annum). Alternatively, government could invest in watershed management and conservation, and pay farmers to limit pollution, at an initial cost of about $250 million and recurring costs of $100 million each year. The savings on purification plants can be viewed as a proxy for the valuation of the regulatory services provided by the watershed.	Global carbon trading: when we want to reduce emissions of greenhouse gases it does not matter whether we plant trees and fix carbon in India, or invest in new technologies in the Netherlands – a tonne of carbon is a tonne of carbon. There is great scope for market instruments to lower the costs of reducing emissions (invest where success is cheap), but progress in fixing carbon is slow and fragile because of significant free-riding incentives.

the ecosystem is placed at risk, the nature and scale of the consequent impacts on the provision of ecosystem services. Where the ecosystem services are dependent on biodiversity, loss of biodiversity can be valued in terms of ecosystem services foregone or reduced, provided that there is a robust description of the relationship between biodiversity and ecosystem services. The quality of the underlying science is therefore of great significance in all kinds of valuations.

4.3.3 Putting valuation into practice

An example of putting valuation into practice has been provided by the UK Department for Environment, Food and Rural Affairs (Defra). Its appraisal of a range of options for a Flood and Coastal Erosion Risk Management (FCERM) scheme includes specific estimates of the economic value of changes in ecosystem services under a range of options, using the 'impact pathway approach'. This involves a series of steps, so that a policy change, the consequent impacts on ecosystems, changes in ecosystem services, impacts on human welfare and economic value of changes in ecosystem services are considered in turn (Defra 2007, p. 22). In this analysis the steps were:

1. establish the environmental baseline;
2. identify and provide qualitative assessment of the potential impacts of policy options on ecosystem services;
3. quantify the impacts of policy options on specific ecosystem services;
4. assess the effects on human welfare;
5. value the changes in ecosystem services (Defra 2007, p. 22).

This approach ensures that key stakeholders in FCERM are broadly supportive of moves towards greater inclusion of economic value estimates in appraisals, despite the remaining uncertainty about the absolute value of the ecosystem services, resulting from uncertainty about both the physical changes in ecosystem services and the appropriate monetary values to apply to these. The authors suggest that 'practical appraisals need to compare the relative magnitude of changes in the provision of ecosystem services across different options' and conclude that 'this can be possible even with limited availability and precision of scientific and economic information. In most cases it should be possible to present a robust assessment, with suitable sensitivity analysis, highlighting the key uncertainties and exploring their implications' (Defra 2007, p. 49).

The prime current example of PES, carbon trading, is developing rapidly. In Europe, the EU Emissions Trading Scheme (EU ETS) is in a second phase of development and now accounts for about 65% of global carbon trading. Current allowance prices for carbon within the EU ETS show some volatility but are currently (September 2008) around €22 (per tonne CO_2 equivalent). Volumes traded average about 8.5 million tonnes per month.

Voluntary offsets also contribute to global reductions of greenhouse gas emissions. These are taken up as companies and individuals seeking to reduce their carbon footprints, motivated by corporate social responsibility or by personal concern. The market in offsets is developing rapidly. Volumes transacted in 2007 were about 65 million tonnes CO_2 equivalent, up from 25 million tonnes in 2006.

The costs of carbon offsets vary widely, reflecting the quality of the offset, with prices ranging from €2 to over €300. The average for 2007 was double the 2006 price, at about €6 (New Carbon Finance 2008).

It seems, therefore, that the methods for valuing ecosystem services and biodiversity are becoming accepted and embedded in a wide range of policy instruments. The results of valuation are also increasingly recognised and accepted in policy debates and in individual decisions, on environmental impacts of projects of economic development, for example. Current knowledge of ecosystem services and the processes behind them gives a strong basis for valuation. However, it is clear that there is much further that can be done to strengthen the underpinning science. Annex 1 summarises some key areas for further work.

4.4 Prioritising ecosystem services in land management: weighing up alternative land uses

The availability of biodiversity-related ecosystem services depends on land use. In Europe, habitat management is usually undertaken for economic or aesthetic/cultural reasons, the latter typically involving biodiversity conservation, focusing on species and/or habitats. At the EU level, conservation of endangered or otherwise valuable natural habitats and plant and animal species is regulated by the Habitats Directive. Although evidence is accumulating that not only biodiversity per se but also the continued provision of essential ecosystem services is vulnerable to land-use change, there has been only weak attention on the impact of land use on ecosystem services. Alternative land uses maximising particular services have rarely been discussed.

In Europe, the status of ecosystems depends on the dominant land use. Natural ecosystems with spontaneous biota develop in conditions without human interference, but are rare in Europe. Human activities such as timber harvesting in forests and grazing of traditional extensive grasslands give rise to semi-natural ecosystems, with an altered structure. Cultivated and urban ecosystems are characterised by the presence of cultivated or introduced species and large changes in ecosystem structure. These broad types of ecosystem, as well as different dynamic stages within these broad types, differ greatly in their capabilities to provide services.

Global scenarios of changes in biodiversity for the year 2100 identified that, for terrestrial ecosystems, land-use change will probably have the largest effect, followed by climate change, nitrogen deposition, biotic exchange and the direct effects of elevated carbon dioxide concentration in the atmosphere (Sala et al. 2000). The type and intensity of land use in Europe have changed dramatically during recent centuries (Poschlod et al. 2005). Historical floras show that the highest diversity occurred around 1850, after which changes in land use have caused a decrease in biodiversity. Major land use changes have included: the intensification of arable field farming from about 1840 owing to the foundation of agricultural chemistry; the abandonment of low-intensity grazing systems and the change to livestock housing; the drainage of wetlands, their amelioration for agricultural purposes and for extracting fuel; and afforestation of the lowlands with coniferous, often non-indigenous trees (Poschold and WallisDeVries 2002). During the latter part of the twentieth century, the 'period of the economic miracle', the decreasing price of energy caused another drastic change. First, the extent of urban and intensively cultivated land increased tremendously. Second, cheap imports of agricultural products from more distant regions caused further decrease of extensive agriculture: these habitats were either converted into more intensively used agricultural systems, were afforested or abandoned. During recent decades, the proportions of forests and urban areas have increased whereas those of arable land and permanent crops have decreased in Europe. At the same time, there has been an increase in the intensity of land use, both in forests, where naturally regenerated old stands are being replaced by conifer plantations, and arable land with increasing use of fertilisers and pesticides. European statistics on the area of semi-natural grasslands and undrained wetlands are not available, but national surveys report a strong decrease in their area.

There have been numerous attempts to find optimal habitat management strategies for particular broad ecosystem types, aiming to maintain biodiversity. In natural ecosystems such as forests, minimal intervention is usually the best habitat management strategy, although different types of sustainable forestry may work as well (Kuuluvainen 2002). In natural aquatic ecosystems, the management of nutrient status of ecosystems is of primary importance (Baattrup-Pedersen et al. 2002), whereas regulation of hydrology is an important issue when managing wetland ecosystems. Optimal habitat management in agricultural ecosystems (Rounsevell et al. 2006) requires the regulation of land-use intensity. There has been much attention on semi-natural grasslands: optimal grazing and mowing regimes, techniques of cutting shrubs and burning, etc. have been discussed (Poschlod and WallisDeVries 2002). However, in all these cases the linkage to delivery of ecosystem services has been weak.

At the same time, there is accumulating evidence of the impact of land-use type and intensity on ecosystem services. For instance, the significance of European semi-natural grasslands as a source of clean and sustainably produced fodder has been recently recognised (Bullock et al. 2007). Those grasslands are extremely rich in species, but also rich in genetic variability within species and may thus provide genetic resources, which might contribute to the development of new breeds of agricultural plants, medical plants, etc. They also provide different regulatory services like pollination (Tscharntke et al. 2005) or hazard prevention (Quetier et al. 2007), or multiple cultural services. The availability of those services is primarily dependent on the continuation of the extensive land use in agricultural landscapes.

Although agri-environment schemes encourage farmers to restore species-rich grasslands on arable land or on culturally improved pastures, the land-use types that maximise ecosystem services are not targeted in the current policies of the EU. The Common Agricultural Policy aims to increase agricultural production, without valuing ecosystem services. Similar policies apply to land use in forest or wetland ecosystems. Current policies also lack a landscape perspective and fail to take into account the linkages between landscape units or the delivery of multiple services from ecosystems. The opportunity for maintaining both ecosystem services and biodiversity outside conservation areas lies in promoting diversity of land use at the landscape and farm rather than field scale (Swift et al. 2004). To achieve that goal, however, would require an economic and policy climate that favours diversification in land uses and diversity among land users.

Current strategies of habitat management and land use in Europe, focusing on economic benefit on the one hand and on the conservation of habitats and species of special interest on the other, now need to be broadened in order to cover a wider range of societal needs. There is therefore an urgent need for policies that prioritise the delivery of ecosystem services from land and that favour appropriate land use, encouraging habitat management and aiming to preserve or improve multiple ecosystem services. Proper ecosystem management strategies have to offer principles for land use in order to minimise the possible conflict between management goals that target different services. Besides traditionally accepted cultural services and more utilitarian services like production of food, fibre and fuel, supporting and regulative services deserve much more attention than they have received until now.

5 Policy options and recommendations

5.1 Introduction: the current policy and management framework

5.1.1 The policy context

Policy-makers need an improved evidence base on which to develop and justify environmental policy. To support the increasing calls for 'an ecosystem-based approach' to environmental management and sustainable development policy more generally, evidence is required to demonstrate the importance of ecosystems in terms of their structure, function and the services they provide to society and the consequent benefits to the economy. These values need to be translated into terms that are consistent with the frameworks within which policy-makers operate, and into measures that enable integration into decision-making frameworks, in particular into economic models.

Although the concept of ecosystem services is widely accepted by natural scientists and some policy-makers, to non-scientists the concept is intangible and it is sometimes difficult for people to translate the theory into terms that are meaningful in their everyday life.

The emphasis of the science has been on improving understanding of the biological, physical and chemical characteristics of different ecosystem types, and the inter-relationships within and between ecosystems. More recently, this emphasis has shifted to understanding the functions of these systems and the respective roles of each of the components. This knowledge needs to be brought together, summarised and translated into terminology and principles that are relevant to policies.

5.1.2 European policy background

Sustainable development is the overarching long-term goal of the EU set out in the European Treaty. In 2001 the European Council set out a strategy for implementing this goal. This strategy has been under review, and a revised 'platform for action' (COM 2005 658 final) was adopted at the June 2006 European Summit. Despite its European Treaty status, sustainable development in the EU has taken a back seat to the goals of economic development. This was highlighted in 2004 when the review of the European Union Sustainable Development Strategy (EU SDS) was delayed to enable the European Commission to undertake the Lisbon Strategy mid-term review. Although the potential of environmental technologies for supporting economic growth are now acknowledged and promoted, the importance of environmental sustainability, and in particular the fundamental role of ecosystems for providing the goods and services on which society and ultimately economic growth depend, has not been yet been acknowledged by the wider European policy community.

The review of the EU Biodiversity Strategy and Action Plans, and the production of the European Biodiversity Communication have similarly fallen low on the EU Policy Agenda, with the Communication appearing a year later than expected. However, now that the Communication has been issued, the profile of biodiversity in the EU is relatively high. Furthermore, the Biodiversity Communication includes within it a proposal for a new EU mechanism for informing implementation of the EU Biodiversity Action Plan and further policy development, and for enhancing research on biodiversity. The preferred option for delivery is to create a secretariat based within the European Environment Agency (EEA) but to support this with groups of independent experts. These groups would respond to requests from the European Commission for advice on matters relating to biodiversity and ecosystem services. This project on the relationship between biodiversity and ecosystem services aims to provide support to these initiatives.

5.1.3 The European management framework

EU concern about the decline of biodiversity culminated in the European Commission 2006 Statement on Biodiversity. The EU's aim is to halt loss of biodiversity by 2010.

The Communication identified four key policy areas:

- biodiversity in the EU;
- the EU and global biodiversity;
- biodiversity and climate change;
- and the knowledge base.

The following priority objectives were proposed in the communication:

- addressing most important habitats and species;
- actions in the wider countryside and marine environment;
- making regional development more compatible with nature;
- reducing impacts of invasive alien species;
- effective international governance;
- support to biodiversity in international development;
- reducing negative impacts of international trade;

- adaptation to climate change;
- strengthening the knowledge base.

The Communication suggests four supporting measures:

- adequate financing;
- strengthening EU decision-making;
- building partnerships;
- promoting public education, awareness and participation.

Although these objectives and measures provide a framework for addressing biodiversity loss, the key objectives of the EU remain the sustainable development objectives set out in the Barcelona Statement. Within this larger framework, environment in general and biodiversity in particular appears less immediate than the needs of economic development in improving quality of life in Europe and is given less weight in policy discourse.

To address this weakness, European policy-makers are looking for a more powerful narrative to link biodiversity to long-term sustainability, and hence to quality of life. This may include an evaluation of the economic importance of ecosystem services.

5.2 Is what is known about this topic sufficient for progress in making policy on European biodiversity?

This review has demonstrated that the services provided to humanity by ecosystems in Europe are many, varied, of immense value, and frequently not open to substitution by any artificial process. Because living organisms are essential components of all ecosystems, it follows that they play a key role in the delivery of the services. In some cases, the presence of organisms is what matters, and typically their physical structure: for example, in stabilising slopes against erosion or coastlines against tidal surges, what matters is that there is vegetation and, as far as is known, the make-up of that vegetation matters less. In these cases, biodiversity appears to play a relatively small role.

However, there are some services where there is clear evidence that the number of types of organisms makes a substantial difference to the delivery of the service. We have highlighted four of these services as being both of key importance to our survival as a society and particularly susceptible to the biological richness of the ecosystems that deliver them: primary production, nutrient cycling, pollination and a set of cultural services centred around ecotourism and recreation. There are other services for which the evidence suggests that biodiversity is important, but these appear to play a smaller role in sustaining modern European societies, at least at present.

Focussing on these services may obscure a more fundamental point: that all ecosystems deliver a broad range of services, for some of which biodiversity is crucial and some of which are of particular economic or social value. A forest can be a major store of carbon, helping to regulate climate; it can be a source of resources for industry in the form of fibre or fuel; it can prevent loss of soil and nutrients, flooding and avalanches; it can play a key role on the water cycle, ensuring cycling of water vapour back to the atmosphere; and it can be a substantial attractant to visitors, boosting the local economy directly.

Two key points arise from understanding that all ecosystems deliver multiple services. The first is that managing an ecosystem primarily to deliver one service will almost certainly reduce its ability to provide others: a forest managed exclusively for timber production will have minimal amenity and ecotouristic value, will store little carbon and will be ineffective at retaining nutrients. The second point is that many of the multiple services that arise from a single ecosystem are either undervalued or completely unvalued: in the case of the forest, society currently places no value on nutrient cycling, only rarely values water cycling and regulation, and is only beginning to find ways to value carbon storage effectively.

Generally speaking, all ecosystem services that do not provide goods that can be handled through conventional market mechanisms are undervalued. Some value is placed on amenity, because of the increasing recognition that the economy of many rural areas in agriculturally marginal zones is heavily dependent on tourism, as dramatically revealed by the 2001 foot and mouth disease epidemic in the UK. No effective values are placed on most of the basic supporting services (soil formation, water and nutrient cycling) and primary production is generally only valued in so far as it creates marketable goods. Regulating services are almost always undervalued, perhaps most notably in the case of pollination, despite the fact that in this case it is possible to understand the value that it provides in relation to marketable goods such as food.

Perhaps the best recent example of a policy failure that arose from considering ecosystem services singly is biofuels. The European target of 10% of motor fuel derived from biofuel was set as a means of reducing carbon emissions from transport. This is a highly desirable goal, but the consequences have been highly undesirable. First-generation biofuels almost never reduce net carbon emissions, and even second-generation approaches may well be ineffective. The problem is that the policy leads to the management of ecosystems for a single service – the production of biomass for fuel – ignoring the other services, such as carbon storage and trace gas regulation performed by the same or other organisms in the same system.

There is an urgent need therefore to provide incentives to managers of land and water to ensure the maintenance of the broad range of services from the ecosystems that they manage. Because of the difficulty of using traditional economic instruments to achieve this goal, as set out in Chapter 4, an alternative regulatory framework is needed. In the narrow case of water, which represents a subset of ecosystem services as discussed here, the EU has tackled the problem by a set of binding legal requirements, the Water Framework Directive. We believe that the EU should move to creating an Ecosystem Services Directive, which would require Member States to give explicit attention to the broad consequences of existing and proposed forms of ecosystem management.

5.3 Recommendations: what is it sensible to do now?

The research that has been assessed in this report demonstrates that both the quality and quantity of biodiversity are important for maintaining the health of ecosystems and their ability to deliver services to society. The importance of biodiversity varies greatly among services, being particularly strong for primary production, nutrient cycling and pollination, for example, but much less so for protection from natural hazards. The way in which biodiversity ensures the processes that underlie ecosystem services is only partly understood, and there is an urgent need for research to determine how great a loss of biodiversity can be experienced before service delivery declines.

We have used the classification of ecosystem services proposed by the Millennium Ecosystem Assessment, but it should not be imagined that these services are delivered individually. All ecosystems provide multiple services, although the relative importance will vary from system to system. Some services, such as nutrient cycling and primary production, are complementary: enhancing one will also enhance the other. Others, however, are potentially conflicting, and there are therefore trade-offs between services. Management of an ecosystem for provisioning services, in particular, tends to reduce their ability to provide regulating and cultural services.

Many ecosystems have been profoundly affected by human activity: intensive agriculture and urban landscapes are prime examples. In intensive agriculture, the focus is exclusively on production of food (or other produce); consequently, a range of other services, from carbon storage for climate regulation through water quality to cultural services, is diminished. This focus on a few provisioning services has arisen because the goods produced in such systems can easily be valued by typical market mechanisms. In contrast, the other services lack markets and although effective ways of valuing them are now available, there has been little attempt to incorporate these methods into economic planning processes, even though many of the currently unvalued services are of fundamental importance to the survival of society and may literally be irreplaceable.

There is therefore an urgent need for European policies to recognise this discrepancy and to provide direct support to the maintenance of healthy ecosystems able to continue to deliver key ecosystem services in a sustainable manner.

One challenging option to encourage land use targeted to the delivery of ecosystem service would be a special EU Ecosystem Services Directive, analogous to the existing EU Habitat Directive that delineates the strategy and targets of biodiversity conservation in Europe. Although the Habitat Directive focuses mainly on biodiversity per se as a cultural service and does not consider the functional role of biodiversity, an Ecosystem Services Directive would aim to create a strategy for the conservation and maintenance of ecosystem functions and the services ecosystems provide not only for the European population, but also worldwide. Like the Habitat Directive, whose Annexes (Annex 1 'Habitat types of Community interest' and Annex 2 'Species of Community interest') set the priority targets of biodiversity conservation, the Ecosystem Services Directive might establish the priorities with the help of two Annexes. We propose that two technical annexes to the Directive need to be developed:

- Annex 1. 'Key ecosystem services of Community interest'. Table 1, especially focussing on services categorised as having high value for the EU, would serve as a draft proposal for such an Annex.
- Annex 2. 'Service providing units of Community interest'. Here we propose to consider both species (Annex 2.1) and ecosystems (Annex 2.2) that are critically important in particular regions of Europe owing to the services they deliver.

The concept of Service Providing Units comes from Luck et al. (2003). Service providing units are populations that are critically important as providers of particular ecosystem services. Although this approach was population-centric, Luck pragmatically suggested that the concept could be extended beyond the population level to include ecological communities. A parallel concept is that of Ecosystem Service Providers by Kremen (2005), which suggests that the services provided by ecosystems are ecosystem-wide or community attributes that can be characterised by the component populations, species, functional groups or habitat types that collectively produce them.

The establishment of a new EU directive is a political decision, which would need to be based on thorough scientific analysis and evidence. We submit this report as the basis for urgent discussion on its feasibility.

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Annex 1 Assessment of the current state of knowledge about European biodiversity and ecosystem services

Ecosystem services

A. Supporting services

These are the basic services that make the production of all the other services possible. They are characterised by long timescales and changes may be slow to take effect.

A1 Primary production

The assimilation of energy and nutrients by organisms.

General significance

Primary production is largely determined by photosynthesis and is a fundamental biosphere property that forms the basis of all ecosystem processes. Primary production shows marked global variation, caused in terrestrial systems by patterns of precipitation, temperature and geology; and in marine systems principally by nutrient supply (upwellings, dust deposition, etc.). There are very strong spatio-temporal gradients in Europe, seasonal, latitudinal and altitudinal. Seasonal variation is especially strong in the north and in arid regions. Richmond et al. (2007) suggest that terrestrial net primary productivity can be used as a proxy for several other ecosystem services and, following Gaston (2000), note that the output of food, timber and fibre tends to be higher in areas with high net primary production, and that at global scales, biodiversity and associated services generally increase with net primary production. Perhaps unsurprisingly, human population density also correlates with primary productivity, leading to a relationship between population density and biodiversity across Europe (Araújo 2003). In other words, people tend to live in the most productive areas, which are also those with greatest biodiversity.

Role of biodiversity

The single largest body of evidence relating diversity to an ecosystem process concerns primary production. Much of the active debate about the impact of variations in biodiversity for ecosystem function and the consequent output of ecosystem services concerns the role of biodiversity in maintaining productivity. The evidence includes theoretical, controlled-environment and small- and large-scale field studies (see, for example, Naeem et al. 1995; Tilman et al. 1996, 1997; Lawton et al. 1998), but there are few data from mature natural ecosystems: Grace et al. (2007) compared a large set of natural ecosystems and suggested that the influence of diversity on productivity is weak when examined at small spatial scales. A meta-analysis of published studies found clear evidence of an effect of biodiversity on productivity, and the effect was strongest at the same trophic level as that where biodiversity was measured (Balvanera et al. 2006). At broad spatial scales, Costanza et al. (2007) showed that over half of the spatial variation in net productivity in North America could be explained by patterns of biodiversity, if the effects of temperature and precipitation were taken into account. They predict that a 1% change in biodiversity results in a 0.5% change in the value of ecosystem services, within the temperature ranges in which most of the world's biodiversity is found. Biodiversity is also associated with enhanced productivity in marine systems (Worm et al. 2006): in a meta-analysis of published experimental data, increased biodiversity of both primary producers and consumers enhanced the ecosystem processes examined; the restoration of biodiversity in marine systems has also been shown to increase productivity substantially.

The primary driver of biodiversity in mature natural ecosystems is frequently the legacy of evolutionary history; the relationship between diversity and productivity is therefore often hard to discern (Pärtel et al. 2007). In many mature natural ecosystems, biodiversity as such may play a small role in controlling productivity, and typically the diversity of functional groups is more important.

In intensively managed and disturbed ecosystems, maximum productivity is typically achieved in systems of very low diversity, for example heavily fertilised monocultures. However, the maintenance of these systems requires large inputs of resource, including fertilisers, biocides and water, which are generally not sustainable, either environmentally or economically. Sustained high production without anthropogenic resource augmentation is normally associated with high levels of biodiversity in mature ecosystems. Bullock et al. (2007) reported positive effects of increased species richness on ecosystem productivity in restored grasslands on a range of soil types across southern England, in an eight-year study. Similarly, Potvin & Gotelli (2008) reported higher productivity in biodiverse tree plantations in the tropics, suggesting that increasing plantation diversity may be a viable strategy for both timber yields and biodiversity conservation.

Evidence for a positive association between the diversity of functional types and productivity is particularly strong in relation to soils. Many experiments have shown significant enhancements of plant production owing to the presence of soil animals, and specifically their diversity in the case of earthworms (Lavelle et al. 2006). The enhancement of primary production might be the result of increased release of nutrients from decomposition, enhancement of mutualistic micro-organisms (van der

Heijden et al. 1998), protection against diseases, and effects on soil physical structure. However, experimentally removing key taxonomic groups from soil food webs often has little impact on rates of processes such as soil respiration and net ecosystem production (Ingham et al. 1985; Liiri et al. 2002; Wertz et al. 2006), possibly because that the exceptional diversity of soil organisms and the relatively low degree of specialisation in many groups means that many different species can perform similar processes (Bradford et al. 2002; Fitter et al. 2005).

The mechanisms underlying the reported relationship between diversity and productivity are unclear. Particular species may play key roles in communities that allow the maintenance of high levels of productivity, for example nitrogen-fixing plants or mutualistic symbionts. More biodiverse communities are inherently more likely to contain such key species or those that contribute disproportionately to the maintenance of productivity, a phenomenon known as a 'sampling effect' (Huston & McBride 2002).

A recent extensive and detailed review (Hooper et al. 2005) concluded that certain combinations of species are complementary in their patterns of resource use and can increase average rates of productivity and nutrient retention. They argue that the diversity of functional traits in the species making up a community is one of the key controls on ecosystem properties, and that the redundancy of functional traits and responses in ecosystems may act as an 'insurance' against disturbance and the loss of individual species, if the diversity of species in the ecosystem encompasses a variety of functional response types.

Ecosystems involved

All ecosystems contain and depend upon primary producers. The highest productivity is typically found in warmer and wetter regions of Europe, and on younger and inherently more fertile soils. Cold (alpine, Arctic), dry (some Mediterranean) and infertile (some sandy soils) ecosystems generally have low productivity. Ecosystems in which productivity is strongly linked to biodiversity may include those under management regimes that involve the harvesting of significant amounts of biomass (and hence nutrients) at regular intervals, including grasslands and forests.

European concerns/context

On a large spatial scale, productivity is likely to decline owing to increased prevalence and severity of drought in parts of southern Europe: the severe heatwave of 2003 resulted in a Europe-wide decline in primary production (Ciais et al. 2005). Air pollution associated with heatwaves will also reduce productivity locally. However, productivity may increase in the north and in alpine regions owing to an extended growing season. Locally, increased nutrient supply (either by deliberate fertilisation or unintended pollution) will increase production, with benefit in agricultural systems but potentially serious damage to natural ecosystems through eutrophication, which causes local extinction of species adapted to nutrient-poor environments. Loss of biodiversity due to land management practices may render ecosystems less resilient to impacts of climate change (for example drought).

Policy implications

Maintaining primary production of agricultural, natural and semi-natural ecosystems is essential for achieving several life-support services and policy goals, including carbon sequestration in soils and vegetation, agricultural production, and use of land for other productive purposes (fuel, fibre, etc; see section on provisioning services). However, current policy offers incentives for unsustainable practices that often prioritise production over other ecosystem services: high levels of fertiliser input supported by Common Agricultural Policy thresholds result in reductions in biodiversity, water quality and other goods. Achieving good levels of agricultural productivity in biodiverse systems will be important in economic development of rural areas to encourage tourism alongside traditional agricultural livelihoods; for example, Bullock et al. (2007) suggest that the re-creation (or preservation) of diverse grasslands of conservation value can increase hay yield over the long term, which will enhance farm incomes.

Research needs

Evidence for role played by biodiversity is stronger here than for most other services. Numerous small-scale experiments have produced largely consistent results. A major research need is for large-scale experiments with natural species assemblages that allow impacts of changes in production on other ecosystem processes and socio-economic variables to be examined. The relationships between diversity, productivity and ecosystem properties such as stability and resilience also remain to be resolved, and there is an urgent need to clarify the mechanisms by which diversity can enhance productivity.

A2 Nutrient cycling

The distribution throughout the ecosphere of the elements essential to life, notably nitrogen and phosphorus.

General significance

Nutrient cycling is a key process in both terrestrial and aquatic systems and is essential for maintenance of fertility. Availability of nutrients that determine productivity (notably nitrogen and phosphorus) is determined by the rate of nutrient cycling. Nutrient cycles are especially sensitive to disruption when the element has a large atmospheric pool (nitrogen and carbon); in these cases, rates of fixation of the element into biomass and its return to the atmosphere through decomposition determine both productivity and atmospheric composition. In marine systems, cycling is determined by a balance of rates of input from land, fixation from atmospheric pools, and upwelling and loss by sedimentation.

Role of biodiversity

Because nutrient cycles include numerous transformations of elements, often involving complex biochemistry, many different species are typically implicated. For example, in the nitrogen cycle, large numbers of bacterial species (both symbiotic and free-living) are capable of fixation of di-nitrogen gas (N_2) from the atmosphere; others are involved in the conversion of ammonium to nitrate (nitrification) and the release of ammonium from organic matter during decomposition; whereas the overall rate of the cycle is closely linked to productivity, in which biodiversity is known to play a large role. Nitrogen cycling may depend on diversity of plant communities and particularly on the presence of particular functional groups. Symstad & Tilman (2001) found a higher rate of nitrogen loss by leaching from a community from which cool-season (C3) grasses had been removed, and Mabry et al. (2008) reported greater capacity of natural woodland to store nutrients and avoid leaching to surface water, compared with disturbed woodland missing one functional group (spring ephemerals). Decomposition rate is also susceptible to variation in plant biodiversity: Chapman & Koch (2007) reported that decomposition rate of needle litter in a coniferous forest ecosystem increased with plant species diversity; and Scherer-Lorenzen (2008) found that diversity of plant functional types determined decomposition rate in experimental grasslands.

In many processes within nutrient cycles, keystone species are involved: for example, heavy-metal contamination, often resulting from use of sewage sludge on land, inhibits the growth of symbiotic nitrogen-fixing bacteria and severely limits the nitrogen cycle (Knights et al. 2001). Some key nutrient cycling processes (for example nitrification) are performed by a few key species. These are defined by Schimel (1998) as 'narrow processes'. In contrast, there are others (for example decomposition of cellulose cell walls) that can be performed by a broad range of species. Narrow processes may be more susceptible to changes in biodiversity than broad ones.

Soil biodiversity has a particularly strong impact on nutrient cycling. Barrios (2007), in reviewing the importance of the soil biota for ecosystem services and land productivity, emphasised positive impacts of microbial symbionts on crop yield, as a result of increases in plant available nutrients, especially nitrogen, through biological nitrogen fixation by soil bacteria such as *Rhizobium*, and phosphorus through arbuscular mycorrhizal fungi. Soil nutrient availability itself affects plant diversity, because of both the direct uptake of nutrients and the feedback effects of plants on soil microbial dynamics and consequent changes in nutrient fluxes (Hooper & Vitousek 1997, 1998; Niklaus et al. 2001).

Nitrogen is the major fertiliser in intensive agriculture, with often dramatic impacts on crop yield, although at rates of application that typically result in large losses of nitrogen to water and to the atmosphere, as ammonia and nitrous oxide, the latter being an especially potent greenhouse gas. However, nitrogen fertiliser is increasingly expensive (about 90% of the cost is energy, typically from gas) and supplies are therefore not sustainable. Biological nitrogen fixation accounts for around half of all nitrogen fixation worldwide, and sustainable agricultural systems will increasingly rely on this process.

Similarly, phosphate fertiliser is routinely added in intensive agricultural systems, but world supplies of rock phosphate are restricted, and typically only 5–10% of added phosphate is recovered in crops, owing to its strong fixation by soils. In natural ecosystems, symbiotic mycorrhizal fungi are the main route of phosphorus transfer from soil to plant, and the diversity of mycorrhizal fungi can regulate both plant diversity and nutrient and, possibly, water use efficiency (Brussaard et al. 2007). Sustainable agricultural systems will need to make greater use of mycorrhizal fungi, whose diversity is currently very low in arable systems (Helgason et al. 1998).

The ability of vegetation to capture and store nutrients is widely exploited in, for example, the establishment of buffer strips to protect water courses from agricultural run-off, and in the construction of reed-beds, as part of water purification measures. Diverse systems appear to be more effective in retaining nutrients within the ecosystem: Engelhardt & Ritchie (2001, 2002) have shown that increased flowering plant diversity enhances productivity and aids the retention of phosphorus in wetland systems, thereby aiding the water purification service.

Nutrient availability depends both on the stock of nutrients in the ecosystem (including the atmosphere) and the rate at which nutrients cycle: some ecosystems with very large stocks (for example of organic nitrogen in organic matter in soil) may nevertheless have low productivity due to low rates of cycling (for example in peat soils), whereas others with small stocks and rapid cycling may be highly productive (for example shallow lakes). Ecosystems may act as large stores of nutrients. It is particularly important to understand the capacity of ecosystems to sequester nutrients when management interventions are contemplated.

Marrs et al. (2007), for example, have shown that bracken has a greater capacity to store carbon, nitrogen, phosphorus, potassium, calcium and magnesium than other vegetation components in the same habitats. As a result, bracken control measures can result in nutrients being released through run-off. This effect poses a dilemma for conservation policies, suggesting 'a need to balance conservation goals against potential damage to biogeochemical structure and function' (Marrs et al. 2007, p. 1045). The example of bracken suggests that the roles of biodiversity and of particular 'keystone' species in communities need to be looked at together.

Ecosystems involved

Nutrient cycling occurs in all ecosystems and is strongly linked to productivity (section 1A), because of the energetic requirements of the nutrient transformations involved and the need for nutrients in all metabolic processes. A key element is nitrogen, which occurs in enormous quantities as the inert di-nitrogen gas in the atmosphere and is converted to a biologically useable form (ammonium) by bacteria, either living independently or symbiotically in roots of some plants, notably legumes. Biological nitrogen fixation is a major source of nitrogen in European ecosystems and tends to be greatest in the early stages of ecosystem development when little nitrogen is stored in soils in organic form. In contrast, the source of phosphorus in natural ecosystems is minerals in rocks. It is progressively lost from soils as they mature, so that very old soils are the most phosphorus deficient.

European concerns/context

Disruption to nutrient cycles can be brought about by atmospheric deposition of nitrogen, sulphur and sometimes metals to soils – through effects including acidification, denitrification, inhibition of fixation – and by sewage, industrial and agricultural effluents in aquatic systems. These are major problems in the EU; they have pronounced effects on natural ecosystems, particularly in heavily industrialised areas. Classic examples include atmospheric nitrogen deposition in the UK and Holland, which has been shown to damage natural ecosystems; and acid and metal pollution in the Czech Republic, Poland and other Member States. The widespread use of sewage sludge as an agricultural fertiliser has resulted in contamination of soils by heavy metals (for example zinc, copper, cadmium), which inhibit nitrogen-fixing bacteria. In intensively farmed landscapes, phosphate may be lost to watercourses, despite the ability of soils to retain and sequester the element, causing both damage to water quality and economic losses on farms. Changes in biodiversity of natural ecosystems brought about by land-use change, climate change or pollution alter the ability of ecosystems to retain nutrient stores, resulting in release of nutrients to other ecosystems with potentially damaging consequences.

Policy implications

Biological nitrogen fixation is of enormous value in agriculture and avoids large-scale addition of nitrogen fertilisers in many agricultural systems. The development of policies on sustainable agriculture will require greater reliance on biological nitrogen fixation and on symbiotic mycorrhizal fungi to gain access to stores of nitrogen (in the atmosphere) and phosphorus (in the soil). Policies that promote soil microbial diversity will be required. Barrios (2007) has argued more generally that we need land-quality monitoring systems that inform managers about their land's ability to deliver ecosystem services, improve capacities to predict and adapt to environmental changes, and support policy and decision-making: currently no recognition is given in EU policies to the nutrient cycling services offered by ecosystems that are not managed for production.

European policies, implemented at United Nations Economic Commission for Europe (UNECE) and EU levels to manage environmental acidification from air pollution could be expected to have a beneficial effect on nutrient cycling. However, there remain large areas of Europe where deposition of sulphur and, particularly, nitrogen exceeds critical loads. Further progress to reduce sulphur and nitrogen emissions, and in consequence deposition, will be needed if the aims of the EU and UNECE are to be achieved. Although the impacts on nutrient cycling are not captured in the current assessment of benefits of these policies, they remain an important additional benefit that should be included in future assessments, for example those made by the International Institute for Applied Systems Analysis (IIASA).

Research needs

We do not know whether the ability of microbial communities in soil responsible for processes of nutrient cycling to withstand anthropogenic inputs such as sulphur (causing acidification), nitrogen (causing acidification and eutrophication) and metals (directly affecting microbial growth and survival) depends on the diversity of the community, especially for 'narrow processes'. Robson (2006) recommends that there is a greater need to:

- Develop models to assess the importance of factors in gas regulation and primary production, genetic exchange and dispersal, nutrient cycling, and the roles of different taxa in the delivery of these processes in marine ecosystems.

- Understand the threshold of tolerance for extreme conditions under the scenarios of climate change, and their potential effects on ecosystem function, for example rates of soil process such as nutrient cycling or shifts in dominant ecosystem processes of primary production and decomposition.

Assimilation of current understanding of the impacts of environmental acidity on nutrient cycling into integrated assessment modelling would provide a further estimate of the value of policies to reduce acidic emissions in Europe.

A3 Water cycling

The distribution of water so that it is available to living organisms throughout the ecosphere.

General significance

The water cycle is an important process in the overall management of water. It affects the distribution of water and the capability of natural processes to condition it for its various functions in the environment and uses for people. The different processes involved in the cycling of water include evaporation, precipitation, the flow of water over and through land and the intervention of people, other organisms and the physical environment in the regulation of those flows. Humans have made massive changes in water cycles through drainage, dams, structural changes to rivers and water abstraction, especially from subsurface reservoirs. Often runoff has become more rapid owing to changes in landscapes, including deforestation, land drainage, urbanisation and engineering works. Many of those impacts are likely to be amplified through climate change, which will result in different patterns of water movement both spatially and temporally, including a greater frequency of extreme events (storms or droughts, for example) and long-term trends in precipitation and evaporation. The dynamics of ecosystems in arid and semiarid climates are strongly dependent on the availability of soil water, and projections of climate change do not encourage optimism for the trajectory of change in much of southern Europe.

Role of biodiversity

Land use and landscape structure are more significant in maintaining this service than biodiversity per se, but both vegetation and soil organisms have profound impacts on water movements (compare with water regulation), and the extent of biodiversity is likely to be important. The influence that different types of habitat have on the rate of water flow through the hydrological system is widely cited in the literature on ecosystem services. For example, Zhang et al. (2007) note that vegetation cover in upstream watersheds can affect quantity, quality and variability of water supply, all of which can affect agricultural productivity. They suggest that maintaining forest cover may not necessarily increase absolute amounts of water retained by the ecosystem: other vegetation may do just as well. Although there is no consistent effect of forest management on storm runoff and erosion (Sidle et al. 2007), forests generally appear to stabilise water flow (Armstrong et al. 1990), thereby reducing the differences in flow between wet and dry seasons.

Distinct pathways of water movement in the hydrological cycle have been encapsulated in the terms 'green' and 'blue' water (Falkenmark et al. 1997; Jewitt 2002). Blue water is the runoff originated from precipitation which generates stream flow at the land surface or forming base flow and groundwater recharge in the subsoil. Green water is stored in the root zone of plants and is the key to water and food security in drought-prone regions. The balance of blue and green water affects critical feedbacks to the water cycle, including the flow of water to the atmosphere both by transpiration from vegetation and by evaporation from soil, lakes and water on the surface of leaves (Röckström et al. 1999). Changes in species composition can affect the balance between green and blue water yields, and native flora may be more efficient at retaining water than exotic species.

Bosch & Hewlett (1982) reviewed evidence from 94 experimental catchments, and concluded that forests dominated by coniferous trees or *Eucalyptus* spp. caused larger changes than deciduous hardwoods on water supply after planting. Subsequent work, mostly outside Europe, has confirmed this relationship; in southern Portugal, Robinson et al. (2006) reported significant local changes in flows, especially in *Eucalyptus globulus* plantations. Invasive plants may divert water resources: the reduction in surface water runoff as a result of invasive alien plants in South Africa may be equivalent to 7% of the national total (van Wilgen et al. 2008), despite active programmes to limit their spread. A key control on the water cycle is the ease with which water penetrates soil. Where penetration is low due to compaction or development of surface crusts, the increased runoff alters the blue:green balance. Soil invertebrates play an important role in the delivery of ecosystem services by influencing soil structure: invertebrates tend to decrease surface runoff by increasing surface roughness and structural porosity of soils (Flury et al. 1994; Lavelle et al. 2006). Flows of water in ecosystems also determine the network structure of rivers that act as ecological corridors for aquatic organisms, including water-borne disease pathogens.

Ecosystems involved

The main problems in Europe arise in the south because of deficit of water and in some central European areas which are frequently flooded. Riverine ecosystems are changing in response to land use and climate change, and many lowland rivers now suffer severe loss of base flow as a result of water abstraction for irrigation. Wetlands and tidal transition ecosystems are threatened all over Europe by drought, drainage or sea-level rise, and the risk of loss of their important ecosystem services is of concern. Urban areas with sealed surfaces provide new challenges as water moves more rapidly to rivers and there is less groundwater recharge. Flood events are predicted to increase owing to climate change (compare with water regulation below). Responses to water deficit are increasingly reliant on fossil water stores, with consequent issues of the sustainability of water cycles.

Policy implications

In a major new development, EU Member States have begun to implement the Water Framework Directive. This major policy initiative covers both surface water and groundwater and has at its core the link between water cycling and the ecological status of catchments. Member States are under obligations to ensure good ecological status within catchments, which creates a major locus for assessments of ecological status and water cycling. A further development in the understanding of the links between biodiversity and water cycling that will give essential added definition to the objectives of the WFD is a policy to manage green water – the water needed for the maintenance of ecosystem functions and processes.

Research needs

Studies of the importance of biodiversity at catchment level in maintaining overall ecological status would support the linkage between the EU Water Framework Directive and emerging biodiversity policy. There is active research on the relationship between vegetation structure and soil moisture distributions affecting composition and groundwater recharge. However, there are important gaps in knowledge on how vegetation will respond to changes in climate and on the importance of species composition, and especially the particular role of invasive species, on water fluxes. The role of form and function of water pathways and their ecological corridors on biodiversity also needs further study. Although it is known that soil biota determine a range of soil properties that play key roles in the water cycle, the impact of functional group diversity or keystone species is not known and hence the significance of the biodiversity of the soil community cannot be assessed.

A4 Soil formation

The formation of soil at a rate sufficient to support a range of provisioning services, including the provision of food, fibres and fuel.

General significance

Soil formation is a continuous process in all terrestrial ecosystems but is particularly important and active in the early stages after land surfaces are exposed (for example after glaciation). The process of soil formation is highly dependent on the nature of the parent materials, biological processes, topography and climate. Soil formation involves the conversion of a mineral matrix, which has limited capacity to support nutrient cycles, into a complex medium with both inorganic and organic components, and solid, liquid and gas phases, in which chemical and biological transformations take place. The progressive accumulation of organic materials is characteristic of the development of most soils and depends on the activity of plants and associated organisms.

Soil formation is fundamental to soil fertility, especially where processes leading to soil destruction or degradation (erosion, pollution) are active. Agriculture in northern and central Europe has been resilient to the decline in productivity encountered in many regions of the world where cultivation has been continuous for long periods. One of the reasons for this is that the soils are young, recently developing after deglaciation, and consequently are able to maintain supplies of essential nutrients from parent materials in the face of continuous depletion.

Soil formation is a continuous process. Rates of soil formation vary greatly, depending on rock type, climate, location and vegetation, but typically lie in the range 0.04–0.08 mm yr^{-1}, which would create soil at a rate of less than 1 cm per century. Soil is also lost by natural processes of erosion, by both wind and water, but at a much slower rate, typically about 0.02 mm yr^{-1}. A major issue for current agricultural methods is that they accelerate soil loss rates to as high as 4 mm yr^{-1}, up to 100 times faster than the rate of soil production. Even without accelerated loss by erosion, loss of soil biota may reduce soil formation rate with damaging consequences. Intensive agriculture can also reduce soil quality in other ways, for example by removal of organic residues so that organic carbon incorporation into soil is less than the rate of decomposition, leading to reduced soil carbon, with nutritional and structural consequences for soil.

Role of biodiversity

Soil biodiversity is a major factor in soil formation: key taxa have large influence, including bacteria, fungi and invertebrates. Some species or groups of species ('ecosystem engineers') have the ability to transform the structure of the ecosystem. The best example of ecosystem engineering in soil is earthworms: by mixing soil, they radically alter its structure and its properties. Vegetation is also important in soil formation; again there are key taxa, such as legumes for their ability to fix atmospheric nitrogen and build up soil nitrogen stores, and deep-rooted species which can bring nutrient elements from the parent material and relocate them to surface layers. There is a lack of empirical evidence on the role of biodiversity per se in soil formation. Soils are among the richest environments on Earth in terms of biodiversity, but there may be no simple relationship between numbers of species and the activity or extent of soil processes. Nevertheless, the composition of biological communities has been shown to be important: what is essential is the presence and activity of a range of functional types.

Soil structure depends on the activity of a wide range of organisms (Brussaard et al. 1997; Lavelle & Spain 2001), A large part the organic material in many soils derives from the faeces of soil animals, and both the gross and fine structure of the soil is determined by biological activity. The separation of soil into horizons is determined by interactions between physical processes, such as leaching, and biological ones, such as worm activity and root exudation. At a fine scale, structure may depend on fungal mycelia, and the activity of mycorrhizal fungi, symbiotic with plant roots, which are the most abundant fungi in most soils, is of central importance (Miller & Jastrow 2000). At an intermediate scale, burrows created by soil animals can act as channels for root growth, water flow and aeration. Much of this structure is destroyed by cultivation, sometimes with damaging impacts on soil fertility; a soil whose structure has previously broken into fine units can rapidly be reconstructed into the large aggregates that promote many soil functions by endogeic earthworm activity (Lavelle et al. 2006).

Ecosystems involved

Soil formation occurs in all terrestrial ecosystems. It is of especial importance in ecosystems that are developing on newly exposed or created substrates (moraines, lava, gravel deposits, etc.), where the build-up of soil fertility depends entirely on biological processes. There will be particular concerns about soils that are subject to intense erosion, by wind or water, where reconstruction of the soil profile and soil fertility again depend on the biologically driven processes of soil formation; these will be found, for example, where arable agriculture is practised on slopes with inadequate conservation measures, and on sandy soils with seasonal vegetation cover.

European concerns

Northern European ecosystems are still in the early stages (10,000–20,000 years) of post-glacial recovery, and consequently soils are often resilient to intensive agricultural use (Newman 1997). Much of the Mediterranean region, however, has older soils with lower resilience that have suffered severe damage and are often badly eroded (Poesen & Hooke 1997). In alpine areas, high rates of erosion may be countered by high rates of soil development.

Policy implications

Soil conservation policies are needed to ensure that soil stocks are retained, and need to be broadened to include soil 'health' guidelines that recognise the importance of soil biological processes in the creation of soil. Policy implications discussed under nutrient cycling (section A2) also apply here.

Research needs

Barrios (2007) suggests that future studies linking soil biota to soil processes and ecosystem services should have increasing focus on hot spots of activity by soil biota, for example the rhizosphere and soil carbon pools. The above-ground consequences of soil biodiversity are strongly dependent on context, such as the types of soil organism considered, the role of plant species in a community (dominant versus rare or subordinate species) and site fertility. Because of this, it has been suggested that new insights from studies on interactions between above-ground and below-ground should be used to improve our predictions of the effects of human-induced environmental changes on biodiversity and ecosystem properties and to enhance the efficiency of human interventions in restoration and conservation efforts (Wardle et al. 2004).

Swift et al. (2004) have argued that a better understanding is needed of the ways in which the functional properties of soil organic matter are influenced by the diversity of organic materials from which it is synthesised, and that this may require the characterisation of the functional groups of organisms necessary to maintain specific ecosystem services. Usher et al. (2006) suggest that a research priority is the need to determine whether there are particular keystone species among the soil biota, which, if lost, will irreversibly damage the soil. Is there some stress threshold beyond which soil function will be irretrievably impaired?

B. Regulating services

Benefits obtained from the regulation of ecosystem processes.

B1 Climate regulation

The role of ecosystems in managing levels of climate forcing gases in the atmosphere.

General significance

Climate is regulated on Earth by a natural 'greenhouse effect' that keeps the surface of the planet at a temperature conducive to the development and maintenance of life. The mechanism for this is well understood: trace gases in the atmosphere, notably water vapour and carbon dioxide, absorb infra-red radiation emitted from the Earth as it is heated by solar radiation, and hence effectively warm the atmosphere. Numerous factors interact in the regulation of climate, including the reflection of solar radiation by clouds, dust and aerosols in the atmosphere. In recent years climate has been changing and the Earth is becoming warmer.

Current change is largely driven by increases in the concentrations of trace gases in the atmosphere, principally as a result of changes in land use and rapidly rising combustion of fossil fuels. The major greenhouse gas (CO_2) is absorbed directly by water and indirectly (through photosynthesis) by vegetation, leading to storage in biomass and in soils as organic matter; the ability of soils to store carbon is a major regulator of climate (Post & Kwon 2000) after 'climate. Other greenhouse gases, notably methane (CH_4) and nitrous oxide (N_2O) are regulated by soil microbes. Marine systems play a key role in climate regulation through physical absorption of CO_2, through photosynthetic carbon fixation and through aerosol production. Acidification of the seas resulting from increased dissolution of CO_2 will have an impact on these processes.

An additional issue is the impact of vegetation on albedo – the reflection of incident radiation by land surfaces. Dark surfaces, especially those covered by evergreen forest, absorb more radiation than light ones. Consequently, afforestation of boreal zones may have a greater warming effect than any reduction resulting from enhanced carbon sequestration. The role of aerosols emitted by vegetation in 'dimming' solar radiation remains to be quantified.

Aerosols have a profound effect on climate, largely by intercepting and scattering radiation and by acting as cloud condensation nuclei, thus reducing the amount of solar radiation reaching the Earth's surface. The production of aerosols by marine systems is well understood and has been taken into account in climate models. However, there is increasing evidence that forests emit substantial amounts of biogenic volatile organic compounds, which can form aerosol particles. Forests are therefore simultaneously sinks for CO_2, sources of aerosol particles and determinants of albedo, and the impact of increased forest growth on climate change is complex (Kulmala et al. 2004).

Role of biodiversity

The interplay between biodiversity and climate regulation is poorly understood. When major change occurs in ecosystems, the time lags in the feedbacks on ecosystem processes that result are important and unresolved. Nevertheless, the global carbon cycle is strongly buffered, in that much of the CO_2 discharged by human activities into the atmosphere is absorbed by oceans and terrestrial ecosystems (Janzen 2004). The problem we face is that the rate of emissions increasingly exceeds this absorption capacity, which is being reduced still further by anthropogenic damage to ecosystem function.

Globally, the largest pool of actively cycling carbon in terrestrial ecosystems is the soil. The loss of soil organic carbon is a particular issue in Europe. It has been estimated that since 1980 the organic carbon content has declined on average by 15% in arable and rotational grass soils, 16% in soils under permanent managed grassland, and 23% in soils on agriculturally managed, semi-natural land. In addition to the consequences for atmospheric CO_2 concentration, such declines have obvious implications for the productivity of soils and their vulnerability to the erosion hazard.

Europe's terrestrial biosphere represents a net carbon sink of between 135 and 205 gigatonnes per year, equivalent to 7–12% of the 1995 anthropogenic carbon emissions (Janssens et al. 2003). This capacity could be increased: carbon sequestration in cultivated soils in Europe could double under improved management practices (see, for example, Smith 2004b), if the management change were permanent (Freibauer et al. 2004) and focussed on areas with high carbon sequestering potential. The most promising measures include: higher organic matter inputs on arable land, the introduction of perennials (grasses, trees) on former arable land used for conservation or biofuel purposes, the expansion of organic (or at least low input) farming, raising of water tables in farmed peatland, and the introduction of zero or conservation tillage. Practices designed to improve the agricultural productivity of peatlands can lead to changes in the above ground vegetation which in turn lead to changes in the carbon cycle (Worrall et al. 2004). At a finer scale, sequestration of carbon in stable aggregates depends on the activity of the soil fauna: the aggregates formed by networks of fungal hyphae and bacterial mucilages are more labile than those formed in earthworm casts (Lavelle et al. 2006). Disruption of these communities by cultivation and loss of soil fauna due to soil degradation will therefore reduce soil capacity to sequester carbon.

The largest single store of carbon in terrestrial ecosystems globally and in Europe is in the peat soils of the boreal and cool temperate zones of the northern hemisphere. The response of peatlands to climate changes is crucial to predicting potential feedbacks on the global carbon cycle (Belyea & Malmer 2004). The climate-regulating function of peatlands also depends on land use because intensification of land use (for example for biofuels production, section C3) is likely to have profound impacts on soil carbon storage and on the emission of trace gases. Considering the area of drained and mined peatlands, peatland restoration on abandoned mined peatlands may represent an important biotic offset through enhanced carbon sequestration (Waddington et al. 2001). However, peatlands are also major sources of methane, a potent greenhouse gas. The biodiversity of soil microbes is not a key determinant of peat-related carbon storage (Laggoun-Defarge et al. 2008), because peat forms when biological activity is minimised, but it is likely to play an important role in trace gas (methane, nitrous oxide) production. Niklaus et al. (2006) found lower N_2O emission rates from the soil of experimental systems with higher plant diversity. However, they concluded that keystone species played a more significant role in determining this than plant species richness per se, but current evidence for the role played by soil biodiversity in key processes leading either to carbon sequestration or to the release of these trace gases (methane, nitrous oxide) is poor.

In global terms, the oceans contain the largest reserves of carbon, but most of this is in deep ocean layers and not in active circulation, at least not in times measured in human generations (Janzen 2004). Nevertheless, the exchange of CO_2 between atmosphere and ocean is larger than that between air and terrestrial ecosystems. Some of this occurs by physical processes, involving the equilibrium between CO_2 and carbonate, but a significant proportion is accounted for by biological processes. Although oceanic plants, mainly algae, account for less than 1% of global biomass carbon, the net primary productivity of the oceans is roughly equal to that of all terrestrial systems.

Ecosystems involved

All soils store carbon, but to widely varying extents. The largest stores are in peatlands, but soils rich in organic matter occur in many ecosystems, especially where low temperature, low pH or waterlogging inhibit decomposition. Forests are the only major ecosystems where the amount of carbon stored in biomass of the plants exceeds that in the soil; deforestation therefore also has the capacity to affect climate regulation. Agricultural ecosystems currently have low soil carbon stores due to intensive production methods, and there is scope for enhancing those stores. Marine ecosystems also play a major role in climate regulation, through carbon sequestration and aerosol emission.

European concerns/context

All soils contain organic matter, which is a major store of carbon, but peat soils have especially high carbon contents. Europe contains extensive areas of peat containing large quantities of carbon. Losses of carbon from these peat (and other) soils could easily outweigh any savings made by reductions in fossil fuel use: UK soils may have lost as much as 0.6% of their stores of carbon each year over the past 25 years (Bellamy et al. 2005). There are concerns over the methodology used in this study, but it illustrates the importance of having good knowledge about the performance of soils in Europe as carbon stores. This is particularly important in the case of peatlands, which have a capacity to sequester substantial amounts of carbon.

There are strong regional variations in trace gas emissions and absorption, and soils across Europe therefore vary in the contribution they make to climate regulation services. There are other new pressures on soils which require assessment as part of an overall system for managing carbon stores in Europe. For example, intensive biofuel production, though it might appear to provide a source of renewable energy, may lead to reduced carbon retention in soils, because the goal will be to remove as much biomass as possible; it will also simultaneously increase emissions of nitrous oxide (N_2O, a potent greenhouse gas) as a result of increased nitrogen fertiliser additions to soils.

Policy implications

The fundamental concern is to ensure that European policies take into account multiple impacts: for example, consequences of changes in land use aimed at increasing biomass production for carbon storage in soils and emissions of greenhouse gases (methane, nitrous oxide). Agricultural policy has a large influence on this area: peatlands, for example, have historically been viewed either as waste land that can be brought into cultivation by drainage, with inevitable large-scale loss of soil carbon to the atmosphere; or as fuel mines, which produce the same result more quickly. Similarly, soil management policies need to account for the benefits that accrue from sustaining or increasing soil carbon sequestration; this will be especially important for any policies that seek to enhance biofuel production from agricultural land, where there is serious potential for negative carbon balance due to losses of stored carbon and increased trace gas emissions from soils.

There is a need to develop a whole-systems ecosystem approach to the management of carbon and the role that biodiversity plays in future climate mitigation strategies. This is particularly important, for example, given the suggestion that expanding woodland cover might make a significant contribution to future climate mitigation strategies. Afforestation may achieve net uptake initially, but a new equilibrium is established once the forests mature and the forest may cease to be a net carbon sink. The role of forests in future emission mitigation strategies therefore depends strongly on their management and the uses of the products that we generate from them, which can ensure that net carbon sequestration can accumulate indefinitely. Forest industries can play a role in shaping more sustainable patterns of both production and consumption, through carbon reserve management and carbon substitution management.

Research needs

We need to understand the long-term potential of carbon sequestration, how much more carbon can be sequestered in terrestrial ecosystems, and how secure is the newly stored carbon. The role of soil micro-organisms in determining rates of key processes in the carbon cycle is central to these questions. We need data on how soil communities react when exposed to a range of anthropogenic stresses, including those associated with agriculture, forestry, pollution and erosion, and the implications these changes might have ecosystem processes. In all of these processes the diversity of the soil community is likely to be important. Forests contribute to climate regulation in complex ways, through carbon storage, aerosol production and control of albedo. We need to discover how biodiversity contributes to these processes.

B2 Disease and pest regulation

Controlling the prevalence of pests and diseases of crops and livestock, and of human disease vectors and disease.

General significance

Disease-causing organisms are normal components of all ecosystems. Their populations are regulated by density-dependent factors such as the activity of their own parasites and predators and the availability and susceptibility of their hosts, the latter dependent on the evolution of defence mechanisms by the hosts. Their populations are also controlled by density-independent mechanisms such as climatic extremes. Despite these regulating and controlling factors, outbreaks of disease occur in all natural ecosystems, though they are usually short-lived. In managed ecosystems, however, diseases are frequently endemic and can only be controlled by human intervention.

Major outbreaks of both human and wildlife (animal and plant) diseases are usually due to the introduction of a new pathogen. The recent appearance of blue tongue disease in cattle in the UK is attributed to the improved survival of the midge that is the vector of the disease organism, whereas sudden oak death is caused by a fungus probably introduced horticulturally. Some ecosystems may be better able to resist invasion by novel pathogens than others, possibly because of factors such as the structure and complexity of ecosystem. The evidence on this is, however, unclear.

Management of diseases can involve several approaches: control of diseased hosts, replacement of susceptible by resistant hosts; ecosystem management to reduce spread of the disease organism; biological control of pathogens; and chemical control of pathogens. Selection pressures on pathogens in many managed ecosystems are now intense: Tilman et al. (2002) have observed that the evolutionary interactions among crops and their pathogens mean that any improvement in crop resistance to a pathogen is likely to be transitory. For example, maize hybrids in the United States now have a useful lifetime of about 4 years, half of what it was just 30 years ago. Similarly, agrochemicals, such as herbicides, insecticides, fungicides and antibiotics, are also major selective agents. Within one to two decades of the introduction of each of seven major herbicides, herbicide-resistant weeds were observed. Insects often evolve resistance to insecticides within a decade. The implication is that in designing future agricultural systems, we need to understand much more deeply what kinds of properties confer resilience to ecosystems, and potentially preserve the wild genetic resource base (see section C6) from which new strategies can potentially be developed.

Some pest organisms are not disease-causing, but rather invasive species that alter the biological community, causing effects such as extinction of native species, disruption of nutrient cycles (for example where the invader is capable of nitrogen fixation), and diversion of water resources. The impacts of invasive alien species on ecosystem services and biodiversity are significant (estimates vary, but the total costs can be in the order of tens of billions of US dollars each year (McNeely 2001; Pimentel 2002; Pimentel et al. 2005).

Role of biodiversity

There is good evidence that the spread of pathogens in managed systems can be reduced by increasing biodiversity. Examples of this phenomenon include the beneficial effect of cultivar mixtures on scab control in apple orchards (Didelot et al. 2007), on control of *Phytophthora infestans* in potato fields (Phillips et al. 2005) and on barley mixtures (see section C1). Similar patterns are seen in natural communities and the theoretical basis of this phenomenon is well understood. There is also consensus that a diverse soil community will not only help prevent losses due to soil-borne pests and diseases but also promote other key biological functions of the soil (Wall & Virginia 2000). Soil-borne pest and diseases such as root-rot fungi cause enormous global annual crop losses (Haas and Défago 2005), but bacteria in the rhizosphere (the soil surrounding roots) can protect plant roots from diseases caused by root-rot fungi (Haas & Keel 2003); similarly, symbiotic mycorrhizal fungi can protect roots from pathogenic fungi (Newsham et al. 1995). Plant-parasitic nematodes represent a major problem in agricultural soils because they reduce the yield and quality of many crops and thus cause great economic losses. However, nematodes have a variety of microbial antagonists that include nematophagous and endophytic fungi, actinomycetes and bacteria (Dong & Zhang 2006). Higher trophic levels in soil food webs can play a role suppressing plant parasites and affecting nutrient dynamics by modifying abundance of intermediate consumers (Sanchez-Moreno & Ferris 2006).

In many managed systems, control of plant pests can be provided by generalist and specialist predators and parasitoids, including birds, spiders, ladybirds, flies and wasps, as well as entomopathogenic fungi (Naylor & Ehrlich 1997; Zhang et al. 2007). For example, in the Netherlands, great tits (*Parus major*) reduced the abundance of harmful caterpillars in apple orchards by 50–99% and increased apple yields (Mols et al. 2002).

Invasive species are found in most ecosystems, but especially those that are most affected by human activity. In the UK, for example, most invasive species are in lowland rather than upland habitats. There is no simple relationship between biodiversity of a community and its susceptibility to invasion: some species-poor communities (for example heathland) have few invasive species. Susceptibility of a community to invasion by exotic species is strongly influenced by species composition and, under similar environmental conditions, generally decreases with increasing species richness (Joshi et al. 2000). However, other factors, such as propagule pressure, disturbance regime and resource availability, also strongly influence invasion success and may override effects of species richness. Hooper & Chapin (2005) caution that by increasing species richness one may increase the chances of invasibility within sites if these additions result in increased resource availability, as in the case of nitrogen-fixers (Prieur-Richard et al. 2002a), or increased opportunities for recruitment through disturbance (see, for example, D'Antonio 2000). It is also possible that high levels of biodiversity may increase the chance of disease outbreaks, by increasing the number of potential hosts, particularly of susceptible as opposed to resistant species, as appears to be the case for sudden oak death in western North America (Condeso & Meentemeyer 2007).

Ecosystems involved

The natural control of diseases and invasions occurs in all ecosystems. Those heavily influenced by human activity incur much the greatest risk of both disease outbreaks and invasion.

European concern/context

Emerging diseases from wildlife are often mediated by intensive livestock production, large-scale movements of people, organisms and products, and often several of these acting together (Christensen 2003). There is therefore an important interaction with food production and distribution systems.

It is likely that climate change will lead to the emergence of new diseases and the exacerbation of existing ones, especially where vectors (for example tick, rodent, mosquito) are favoured by a warmer climate. Diseases such as Lyme disease and West Nile disease are likely candidates, but there are as yet few or no clear cases of disease spread linked to climate change (Zell 2004). However, if pathogen spread does occur, then the interaction with new potential hosts may offer new evolutionary opportunities and lead to the emergence of pathogens with distinctive virulence (Pallen & Wren 2007).

One consequence of increased pest and pathogen impact due to environmental change will be a pressure for greater use of agrochemicals. European policy on chemicals has had a significant impact on the development of new agricultural pesticides. There is potential for the development of European applications of biological control, exploiting the properties of pest regulation in the ecosphere and taking models from the structure of resilient ecosystems.

Most of the invasive plant species likely to emerge in Europe over the next decades are almost certainly already present, grown in cultivation, often in gardens. Many current invasives, such as Himalayan balsam (*Impatiens glandulifera*) and Japanese knotweed (*Fallopia japonica*), were introduced by this route. Some garden species are beyond the limits of their climatic tolerance for survival and reproduction in the wild, but may evolve wider tolerance as the climate changes.

Policy implications

Most pests and pathogens are kept in check in intensive agriculture by application of agrochemicals. Future agricultural policy may need to rely on less invasive control measures and to use the potential benefits of increased biodiversity in disease control. Pest regulation services have the potential to support EU policies on pesticide use by providing alternative strategies for the control of agricultural pests. Such strategies might involve different levels of intervention, including the use of semi-managed ecosystems such as field margins.

There may need to be closer controls on the movement of species into and around Europe if invasive problems are to be avoided, although many future invasive species are already present in Europe and will not become problematic until environmental change or evolution favours their spread; other future problem species will arrive without human intervention.

Research needs

Although there is a good understanding of the way in which pathogens spread through populations, application of this research to practice lags behind. Hooper & Chapin (2005) suggest that integrating results from field surveys with results from within-site experimental manipulations and mathematical models is important for both theoretical understanding and broad-scale management of invasions by exotic species (Levine & D'Antonio 1999; Levine 2000; Shea & Chesson 2002). There is a considerable body of research into biological control of agricultural and public health pests, mainly in tropical systems, which could usefully be assimilated into emerging strategies for low-intervention farming systems.

As in many examples, knowledge of interactions between soil organisms, pathogens and invasive species is inadequate, despite the fact that many serious disease-causing organisms are soil inhabitants.

B3/C2 Water regulation and purification

The maintenance of water quality, including the management of impurities and organic waste, and the supply of clean water for human and animal consumption.

General significance

Natural systems play a major role in controlling the supply of water and in making it fit for consumption. Rates of flow of water from catchments into lowland areas are determined by many factors, including penetration, storage and overland flow. Soil state, climate, vegetation and their interrelations act as key regulators. However, vegetation itself is determined by availability of water in arid and semi-arid areas, giving rise to concern about climatic fluctuations and change. Changing land use, including loss of forest cover and increased drainage, is a major factor, as is changing climate, especially if it leads to greater frequency of high-intensity rainfall events and altered seasonality in rainfall distribution. There are also links between this service and soil erosion (see section A4).

Quality of water depends on a range of factors, including travel through soil and other porous formations before release into water bodies, because the microbial processes in sewage works are effectively replicated in soil. Changes to water quality that occur in soil include the transformations of persistent organic pollutants (POPs), sequestration and conversion of inorganic ions (nitrate, phosphate, metals), and removal of disease-causing microbes such as *Cryptosporidium* (Lake et al. 2007). Similar processes occur in water bodies, including lakes and rivers. There is a strong link between regulation of water supply and water quality, because rapid flows of water through soil or water bodies reduces the time for transformations to occur; extreme weather events thereby lead to poorer water quality. Unsustainable use of water resources, such as excess withdrawals forcing saltwater intrusion in coastal aquifers, may also imperil water quality for several uses of societal importance.

Role of biodiversity

Although vegetation is a major determinant of water flows and quality, and micro-organisms play an important role in the quality of groundwater, the relationship of water regulation and purification to biodiversity is poorly understood, except in so far as the states of soil and vegetation determine water flows and storage. The activity of soil organisms has a large and direct impact on soil structure and hence on infiltration and retention rates (compare with section A3). However, it is likely that many of the key transformation processes in soil are 'broad' processes, in the sense that they can be performed by a variety of common soil microbes, including pseudomonads. On the other hand, where novel compounds such as pollutants are concerned, it is more likely that particular microbial species have the ability to improve water quality, and these should be regarded as 'narrow' processes in which biodiversity may play a large role.

Ecosystems involved

Water reaches freshwater stores (lakes, rivers, aquifers) by a variety of routes, including direct precipitation, surface and subsurface flows and human intervention. In all but the first case, the water quality is altered by the addition and removal of organisms and substances. Ecosystems therefore play a major role in determining water quality. In particular, the passage of water through soil has a profound impact, both through the dissolution of inorganic (for example nitrate, phosphate) and organic (dissolved organic carbon compounds, pesticides) compounds and the modification of many of these by soil organisms. This service is therefore relevant to all terrestrial ecosystems, but may be of particular significance in urban and intensively managed ecosystems.

European concerns/context

In lowland Europe, many factors impinge on water regulation and purification, including the use of floodplains, river engineering and the increasing impermeability of land surfaces in urban areas, leading to rapid runoff and reduced infiltration of water into soil. Nearly 80% of Europeans live in urban areas, in which traffic and industry emit substantial amounts of pollutants (metals, nutrients, organic toxins) which are washed with rainwater from the sealed surfaces directly to surface waters. Sealed soils cannot purify contaminated water and the distorted hydrological cycle impacts not only the city but also surrounding ecosystems. Removal of pollutants (both toxins and nutrients) is therefore a key issue, and there are emerging problems, including the increasing use of biochemicals and pharmaceuticals, the spread and appearance of disease organisms such as *Cryptosporidium*, and increasing input of dissolved organic carbon (apparent as brown colouration) in areas where water supply comes from peat catchments. All these challenge the ability of natural systems to continue to purify water to an acceptable level, at a time when water treatment utilities throughout Europe are struggling to meet the demands of new standards for domestic water supply. The use of the water purification services of natural ecosystems has the potential to ease this pressure by reducing intake loads of contaminants.

Both water availability and water quality need to be secured, with equitable access. The EU as a whole has sufficient water, but projections for both the south and the north under climate change suggest this situation may not persist. Increasingly, freshwater supplies are a problem in the Mediterranean region and in such densely populated areas as southeast England. The impacts of the consequent pumping from groundwater bodies can have a damaging impact on the base flow of rivers and on saltwater intrusion in coastal aquifers. There will therefore be increasing demand to redistribute water, which by itself has major impacts on both biodiversity and other ecosystem functions.

There will be an increasing need to develop production systems based on increased efficiency of water use. Tilman et al. (2002) estimate that globally 40% of crop production comes from the 16% of agricultural land that is irrigated; in parts of the southern EU Member States, up to 90% of agriculture is dependent on groundwater, and, overall, agriculture is estimated to require twice as much water in the next few decades (Schiermeier 2008). The effects of water shortages therefore are already shifting attention from health and sanitation to key economic activities such as agriculture and energy production.

Policy implications

Most policy implications are not closely related to issues of biodiversity, but there is a need for trans-boundary approaches to catchment management: a balance between engineered and ecosystem-based approaches to water regulation. The EU Water Framework Directive tends to treat groundwater and surface water systems as separate compartments. A more coherent approach to the managed recharge of groundwater, with controls on groundwater extraction rates to protect surface ecosystems, would be a valuable enhancement of the WFD.

Rates of urbanisation, especially in new Member States, highlight the need for planned developments to minimise damage to water cycles. There is also a need for more coherent policies on the use of water in agricultural production and on the relationships between groundwater and surface water. In general, the need is for sustainable development practices.

Research needs

In relation to biodiversity, the principal area of uncertainty is in the role of diverse communities of soil microbes in the removal of contaminants from water.

B4 Protection from hazards

Reduction of the impacts of natural forces on human settlements and the managed environment.

General significance

Many hazards arising from human interaction with the natural environment in Europe are sensitive to environmental change. Examples include:

- flash floods due to extreme rainfall events on heavily managed ecosystems that cannot retain rainwater;
- landslides and avalanches;
- storm surges due to sea-level rise and the increasing use of hard coastal margins;
- air pollution due to intensive use of fossil fuels combined with extreme summer temperatures;
- fires caused by prolonged drought, with or without human intervention.

Other hazards, particularly those with geological causes that are localised to areas known to be vulnerable, such as volcanic eruptions and earthquakes, are not relevant to a consideration of biodiversity effects.

Role of biodiversity

The role of biodiversity in delivering protection from natural hazards is generally small. In some cases, the integrity of the affected ecosystem is of central importance, and it is likely that loss of biodiversity may reduce resilience. Biodiversity plays a key role in the preservation of wetlands and tidal landforms that deliver significant ecosystem services throughout Europe. For example, sea-level rise places intense selective pressures on halophytic vegetation whose fate is critical to the survival of saltmarshes and other transition ecosystems, as shown by Marani et al. (2004) in the lagoon of Venice. Soil biodiversity may play a role in flood and erosion control through affecting the surface roughness and porosity (Lavelle et al. 2006). Trees, for example on the boundaries of parks, have been shown to reduce the levels of air pollutants within parks during episodes of high pollution, and incidence of asthma has been shown to be reduced in tree-rich urban areas. Whether biodiversity plays a role (that is, whether it matters which tree species are planted) is unknown. In mountain forests, increasing tree diversity is believed to enhance the protection value against, for example, rockfall (see, for example, Dorren et al. 2004).

Ecosystems involved

Flooding is a problem in a wide range of ecosystems, including steep deforested catchments, flat alluvial plains and urban ecosystems with constrained water flows. Flooding can also occur because of exceptionally high tides and storm surges, a problem that will be exacerbated by rising sea levels; coastal wetlands are known to play a major part in defence against tidal flooding. Wind breaks from managed woods or from the use of natural forest features are a traditional means of protecting crops and habitations against both violent storms and general damage from exposure of high winds. In all these cases the role of vegetation is structural, and the part played by species composition will normally be indirect, in controlling the stability and resilience of the system.

European concerns/context

Increased levels of urbanisation and more intensive use of land for production may reduce the ability of ecosystems to mitigate extreme events. Coastal protection is an increasingly serious issue as sea level rises. Increasingly, protection will depend on 'soft' defences (salt-marshes, etc.) rather than hard coastal defences.

Policy implications

Non-engineering solutions to coastal protection will be increasingly important, and the maintenance of forest cover in steep catchments is essential.

Research needs

There are no research imperatives in this field; where possible roles of biodiversity emerge (as in the recently discovered impact of trees on asthma incidence), follow-up research to identify the role of different species in the response will be required. The principal area of research on biodiversity in relation to natural hazards is to elucidate the role that it plays in regulating the resilience of ecosystems and their ability to withstand environmental change and disturbance.

B5 Pollination

The use of natural pollinators to ensure that crops are pollinated.

General significance

Pollination of flowers by insects is an essential part of sexual reproduction in 90% of all flowering plant species (Kearns et al. 1998); others – including many trees and all grasses, including cereals – are pollinated by wind, whereas a few species are pollinated by other vectors such as water or birds. Habitat destruction and deterioration, together with increased use of chemicals, has decreased abundance and diversity of many insect pollinators. There are examples of crop loss with severe economic consequences in the United States, for example, in almond production. In the USA, 30% of food supply depends on animal pollination (Kremen et al. 2002), and the pressures on pollinators may result in decreased crop production in Europe as well as reduced fecundity of plants, including rare and endangered species.

Role of biodiversity

Crop pollination is perhaps the best-known ecosystem service performed by insects (Zhang 2007; see also Losey & Vaughan, 2006). Over 75% of the world's most important crops and 35% of food production is dependent upon animal pollination (Klein et al. 2007). Bees are the dominant taxon providing crop pollination services, but birds, bats, moths, flies and other insects can also be important. Pollinator diversity is essential for sustaining this highly valued service, which Costanza et al. (1997) estimated to be worth about $14 per hectare per year.

Hajjar et al. (2008) argue that the loss of biodiversity in agro-ecosystems through agricultural intensification and habitat loss negatively affects the maintenance of pollination systems and causes the loss of pollinators worldwide (Kearns et al. 1998; Kremen and Ricketts 2000, 2004; Richards 2001; Kremen et al. 2002). Richards (2001) reviews well-documented cases where low fruit or seed set by crop species and the resulting reduction in crop yields has been attributed to the impoverishment of pollinator diversity. There is increasing evidence that conserving wild pollinators in habitats adjacent to agriculture improves both the level and stability of pollination, leading to increased yields and income (Klein et al. 2003). Several studies from Europe and America have demonstrated that the loss of natural and semi-natural habitat, such as calcareous grassland, can impact upon agricultural crop production through reduced pollination services provided by native insects such as bees (Kremen et al. 2004).

Biesmeijer et al. (2006) examined the evidence for parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands, based on almost one million records for all native bees and hoverflies in both countries. Compared with the period up to 1980, bee abundance has declined in both Britain and the Netherlands, but that pattern is only found for some species of hoverflies in some locations. In both countries, pollinators with narrow habitat requirements showed the greatest declines, and in Britain, plants most dependent on insect pollinators (obligatorily out-crossing species) were declining, whereas wind- and water-pollinated species were increasing and self-pollinating species were broadly stable. Although it is difficult to determine whether the decline in insect-pollinated plants precedes the loss of pollinators or vice versa, taken together they suggest a causal connection between local extinctions of functionally linked plant and pollinator species.

The EU Rubicode programme highlights the importance of traits in biodiversity. One example quoted is the need for diversity of traits such as tongue length and colour attraction in pollinators. This approach is supported by evidence that pollinator diversity, though not abundance, is positively related to seed set in pumpkins (*Cucurbita moschata*) (Hoehn et al. 2008).

Ecosystems involved

All ecosystems, though possibly least important in species-poor boreal forests, where most species are wind-pollinated. However, there will be rare and possibly endangered species in all ecosystems that are potentially vulnerable to declines in pollinator activity. Greatest economic losses will be encountered in agro-ecosystems where insect-pollinated crops are grown and are dependent on wild pollinators.

European concerns/context

Reduction of landscape diversity and increase of land-use intensity may lead to a reduction of pollination service in agricultural landscapes (Tscharntke et al. 2005; Öckinger & Smith 2007). Decreased pollinator services may endanger rare plant species. Semi-natural open habitats (including forest edges and hedges) are under threat throughout Europe; these habitats are essential to the maintenance of vibrant populations of pollinating insects, especially bees, but also hoverflies, butterflies, beetles and other pollinators.

Policy implications

There is a need to maintain diverse landscapes that create networks of open habitats which will encourage reservoirs of pollinators and provide resilience to environmental change. Critical habitats include long-term fallow, which has been largely eliminated in the rush to biofuel production, low-intensity grassland, hedges, and forest and woodland edges. There should also be encouragement of bee-keeping, using native bee species, and careful consideration given to the regulation of pesticide use.

Research needs

We need better data on the effects of landscape composition and configuration on pollinator diversity and abundance, in particular whether there are thresholds for amounts of natural habitat adjacent to crops to provide pollination services. Flowering crops (such as oilseed rape, clover and alfalfa) and forms of agriculture that allow weed survival (as often in organic agriculture) may be important in promoting bee densities.

Pollination is often assumed not to be a limiting factor in either cultivated or wild plants, so establishment of its relative importance for yield or plant fitness is an important research gap, as is understanding the importance of pollinator diversity, especially for creating resilience to change and in the maintenance of biodiversity. The importance of this question is emphasised by recent marked declines in pollinator abundance, particularly in populations of honey-bees, which remain unexplained and are an urgent research need, in terms of both causes and consequences.

Climate warming is already markedly altering flowering times for most plant species (Fitter & Fitter 2002), but there are few data on the parallel responses of pollinators or whether differences in the responses of plants and pollinators could have large-scale impacts on natural communities.

C. Provisioning services

C1 Food

The delivery and maintenance of the food chain on which human societies depend.

General significance

Food production is critically dependent on primary production (q.v.; section A1) and on all the other supporting services (nutrient and water cycling, soil formation) as well as on regulating services (for example pollination). Heywood (1999) estimates that well over 6000 species of plants are known to have been cultivated at some time or another, and many thousands that are grown locally are scarcely or only partly domesticated, whereas as many, if not more, are gathered from the wild. These figures exclude most of the 25,000 species that are estimated to have been used or are still in use as herbal medicines in various parts of the world. However, only about 30 crop species provide 95% of the world's food energy (Williams & Haq 2002) and it has been argued that the world is currently over-dependent on a few plant species. Diversification of production and consumption habits to include a broader range of plant species, in particular those currently identified as 'underutilised', can contribute significantly to improved health and nutrition, livelihoods, household food security and ecological sustainability (Jaenicke & Höschle-Zeledon 2006; Proches et al. 2008).

Role of biodiversity

Intensive agriculture, as currently practised in Europe, is centred around crop monoculture, with minimisation of associated species such as insects and fungi, some of which are pathogenic and able to have large impacts on yield. These systems offer high yields of single products, allowing economically efficient relationships between producers and distributors; they also depend on heavy use of fertilisers and pesticides, raising questions about economic and environmental sustainability. However, some agricultural systems based on a diversity of varieties are more robust and responsive (Hajjar et al. 2008). More diverse production systems may allow farmers to:

- respond to changing market demands or environmental variations that might affect crop production (Vandermeer 1995; Brush and Meng 1998; Gauchan and Smale 2007);
- command price premiums for high-quality traditional varieties that compensate for lower yields (Smale 2006);
- meet social and cultural obligations (Latournerie-Moreno et al. 2006).;
- improve dietary diversity and improve nutrition (Johns and Sthapit 2004).

Diverse systems also seem to be associated with reduced pathogen attack (q.v.; section B2) and application of pesticides, whereas Hooper & Chapin (2005) note that diversity of pasture species can reduce nutrient leaching, production variation, and insurance costs. Thus diversity is consciously incorporated into ecosystems managed for extraction of food and fibre as a safeguard against risk, to optimise use of resources and to provide multiple goods and services. Intercropping and agroforestry studies have frequently demonstrated benefits arising from complementarity or facilitation among crop or forestry species, a response that matches findings from many ecological experiments.

Farming communities outside Europe value the diversity of 'landraces', farmer-developed populations of cultivated species that show among- and within-population diversity and which are linked to traditional cultures (Negri 2004). In southern Mexico, farmers rely on growing a diversity of maize land races because of heterogeneous soil and production conditions, risk factors, market demand, consumption, and uses of different products from a single crop species (Bellon 1996); whereas in Turkey farmers grow different types of wheat in different agronomic conditions or for different uses (Brush & Meng 1998). Moreover, farmers rely on the diversity of other farms or communities to provide new seeds when a crop fails and seed is lost or to renew seed that no longer meets the farmer's criteria of good seed (Louette & Smale 2000). In contrast, few farmers in Europe use land races and most are no longer conscious of the importance of diversity in agricultural production. However, Padulosi et al. (2002) report the case of hulled wheat, a collective name for *Triticum monococcum*, *T. dicoccum* and *T. spelta*, which are an important speciality crop in Italy and other European countries, where both *ex situ* and *in situ* conservation strategies are being attempted.

Failure to maintain sufficient genetic diversity in crops can incur high economic and social costs. The potato famine in Ireland in the nineteenth century is generally attributed to the low genetic diversity of potatoes there, making the crop susceptible to potato blight fungus, a problem resolved by using resistant varieties from South America, where the potato had originated. Barley mixtures may successfully reduce disease incidence in Europe, and so increase yields (Hajjar & Hodgkin 2007), whereas there is potential to use mixed soft wheat varieties for energy-efficient feedstock for the bioethanol industry in the UK (Swanston & Newton 2005). Other examples of the use of varietal mixtures in Europe, North America, Asia and South America are reviewed in de Vallavieille-Pope (2004). However, there is much variation among these studies, and sometimes conflicting conclusions can be drawn about the benefit of varietal diversity. Agricultural strategies need to be tailored to local conditions, including field size and the spatial arrangement of strains.

Hooper & Chapin (2005) argue that maintenance of high productivity over time in monocultures almost invariably requires heavy and unsustainable subsidies of chemicals, energy, and capital. They suggest that diversity becomes increasingly important as a management goal, from both economic and ecological perspectives, with increasing temporal and spatial scales and for providing a broader array of ecosystem services. Some types of farming system in Europe can promote biodiversity. Organic farming can increase biodiversity (species richness and abundance), but with inconsistent effects among organisms and landscapes (Bengtsson et al. 2005): benefits are greatest in intensively managed agricultural landscapes. Even though crop yields may be 20% lower in organic systems, inputs of fertiliser and energy were reduced by 34–53%, and pesticide input by 97%, suggesting that the enhanced soil fertility and higher biodiversity found in organic plots may render these systems less dependent on external inputs (Mader et al. 2002). However, use of land for non-intensive agricultural production is likely to reduce yields and there is then a trade-off between land for agriculture and land for wild biodiversity: we could devote spare land to biodiversity by using intensive agriculture or use more land for production in extensive or organic systems that promote biodiversity.

Ecosystems involved

Food is produced principally in intensively managed agro-ecosystems, comprising 45% of the EU's land area at present, down from 49.5% in 1995. However, there are large areas of Europe in which food production is achieved with less impact, including extensive areas of uplands devoted to grazing, principally by sheep, and large areas, again principally in areas of complex topography, where more traditional forms of agriculture still function. Apart from areas devoted to wildlife conservation or recreation, those used for other production systems (for example forestry) and urban areas, most of the European landscape is involved in food production to some extent. Even some urban and suburban areas have allotment and other forms of garden that are used for food production.

The ubiquity of agricultural production in Europe also means that other ecosystems are frequently adjacent to food-producing land, and processes and practices of agriculture may therefore have a broader impact. Obvious examples of this phenomenon are spray drift and nutrient pollution, both of which can damage semi-natural habitats. Agro-ecosystems may also act as barriers to the migration and dispersal of organisms among remaining patches of non-agricultural land, with negative consequences for the ability of distributed populations to withstand environmental change.

European concerns/context

Currently, although the EU is a net exporter of food in many agricultural sectors, notably cereals, the pattern of trade is such that the EU is actually highly dependent on imports, not simply for fruit and vegetables, but also for some key high-value products within other sectors. The high dependence of European food supplies on imports of some critical parts of the European diet raises important questions about food security and exposes EU citizens to risks associated with both supply and cost. Dependence on imports potentially imposes large carbon costs on the food supply chain, although full life-cycle analysis may reveal that importing food from countries with more productive climates is more carbon-efficient in some cases.

Policy implications

As world food prices rise, there will be pressure to maximise the area under production and this will have potentially devastating impacts on biodiversity. Green et al. (2005) argue that farming is already the greatest extinction threat to birds (the best-studied group), and its adverse impacts look set to increase, especially in developing countries. They suggest therefore that we need to consider the overall effects of different production strategies on biodiversity and compare a 'wildlife-friendly farming' with a 'land sparing' option that minimises demand for land by maximising yields. They conclude that athough the evidence base is incomplete, current data suggest that for a wide range of species in developing countries, high-yield farming combined with areas set aside for biodiversity conservation may allow more species to persist overall. On the other hand, a sustainable solution to this conflict between food production and biodiversity conservation may be to recognise that, although some areas will need to be protected from agricultural exploitation, agro-ecosystems too will need to be managed so as to garner the benefits of biodiversity.

There is therefore a need for a Europe-wide assessment of the impacts of changing land-use. The EU is in a unique position to assess the costs and benefits of alternative approaches to land-use management and make sound choices at the right scale. This will involve ensuring that evolving agricultural support policies and farm payment systems properly value the full range of ecosystem services delivered by agricultural land, and do not focus purely on food production. Other services such as nutrient cycling, water quality and regulation and carbon storage will need to be viewed as of equal status in management of agro-ecosystems.

Research needs

Agriculture meets a major human need, and both affects and depends on all other life support systems. Current trends point to continued human population growth and ever-higher levels of consumption as the global economy expands. This will stress the capacity of agriculture to meet food needs without further sacrificing the environmental integrity of local landscapes and the global environment. Agriculture's main challenge for the coming decades will be to produce sufficient food and fibre for a growing global population at an acceptable environmental cost. This challenge requires an ecological approach to agriculture that is largely missing from current management and research portfolios. Crop and livestock production systems must be managed as ecosystems, with management decisions fully informed by environmental costs and benefits. Currently, too little is known about important ecological interactions in major agricultural systems and landscapes and about the economic value of the ecosystem services associated with agriculture. To create agricultural landscapes that are managed for multiple services in addition to food and fibre will require integrative research, both ecological and socioeconomic, as well as policy innovation and public education.

In the USA, Swinton et al. (2006) have emphasised that despite the artificiality of agro-ecosystems, they have great potential to expand the supply of ecosystem services compared with semi-natural systems. They argue that this is because much more is known about the biophysical relationships within them and we already have precedents for ways to intervene through markets or regulatory mechanisms. They also suggest that on grounds of past performance, agricultural systems have the capacity to respond to such external drivers. A similar argument probably exists for agricultural landscapes in Europe. However, higher levels of biodiversity, especially in soil, may be essential if less energy-intensive forms of agriculture are to be adopted in future, and research on critical levels of soil biodiversity is urgently needed.

C3 Energy

The supply of plants for fuels.

General significance

Natural systems provide a great diversity of materials for fuel, notably oils and wood, that are directly derived from wild or cultivated plant species. In some parts of Europe, gathering of wood for fuel remains an important domestic energy source. There is currently intense interest and strong policy direction to increase the proportion of energy derived from renewable sources, of which biological materials are a major part. At present, this is being achieved partly by the cultivation of biomass crops (for example willow, *Miscanthus*) which are burned as fuels in conventional power stations, and partly by diversion of materials otherwise useable as food for people or animals, including wheat and maize, to manufacture ethanol as a replacement for petrol and other oil-derived fuels. The expectation is that these 'first generation' fuels will be displaced – at least for ethanol production – by a second generation of non-food materials, principally cellulose and lignin from both food crops and dedicated energy crops. However, in the absence of substantial subsidy, the economic viability of second-generation biofuels depends on improvements in enzymatic degradation processes and probably the development of high-value product separation during processing.

All of these biofuel production systems present serious sustainability issues. There are already established damaging impacts on food production and availability and on prices worldwide; in addition, full analyses of the carbon fluxes and other environmental impacts associated with current and envisaged biofuel production systems show that the carbon mitigation benefits are either much smaller than anticipated or even illusory. Several factors that have not been properly assessed in formulation of existing policies undermine the apparent benefits, including: losses of carbon from newly cultivated soils; destruction of vegetation when new land is brought under the plough; losses of other greenhouse gases such as nitrous oxide from nitrogen-fertilised biofuel production systems; and transport and manufacturing emissions.

Many believe that the only sustainable and economically viable biofuels will be a 'third generation', probably utilising single-celled marine algae, grown in saline water in areas where reliable high solar radiation fluxes are available.

Role of biodiversity

It seems unlikely that biodiversity of the crop will play a direct role in most biofuel production systems, although all land-based biofuel production will rely on the supporting and regulating services, such as nutrient and water cycling, for which biodiversity of soil organisms is important. The exception is the proposal to use mown grassland as a second-generation biofuel; sustained production in such a system may well be best achieved by a diverse mixture of plant species (compare with section 1a, primary production).

There may be a need to trawl widely for potential biofuel crop species and algae, emphasising the need to maintain and conserve genetic diversity. However, land-based biofuel production systems have the potential to be especially damaging to conservation of biodiversity because their introduction on a large-scale will inevitably lead both to more intensive land use and to the conversion of currently uncultivated land to production. Much of the damage seems likely to be inflicted outside Europe, particularly in tropical regions, but it will be European demand for biofuels that will be at least partly responsible.

Ecosystems involved

Ecosystems likely to be used for biofuel production include forests, arable land generally and grasslands.

There is likely to be strong pressure to bring land currently regarded as marginal for agriculture into production for biofuel production; because time-to-market issues are less important than for food production systems, remote and relatively inaccessible areas where land values are low may be targets for biofuel systems, introducing conflicts with recreation and biodiversity conservation.

European concerns/context

Energy strategy in Europe currently includes a significant biomass element. However, full carbon budgets for biomass energy production are unknown and it is not clear that there are net benefits in the use of any kinds of biomass.

Biomass for power production and fuel (biodiesel) is likely to become a significant land-use pressure in parts of EU, and the implications of this for other types of land use and for food prices are unknown. In some parts of the EU, peat is used as a fuel in power stations; this is an inefficient way to generate electricity, returns soil carbon directly to the atmosphere as carbon dioxide, and is exceptionally damaging to a restricted and sensitive ecosystem.

Policy implications

The EU should undertake a full audit of implications of increased biomass and bioenergy production, including the full carbon budgets (covering transport, soil carbon storage, emissions and all other flows of carbon), the impacts of expanded biofuel production on biodiversity, and the likely use of genetically modified crops in biofuel systems. There should be an immediate re-assessment of the EU biofuels provisions, and future policy should have a strong and explicit evidence base, and be developed on clear sustainability criteria. The use of peat as a fuel should be discouraged.

Research needs

The most urgent need is for whole life-cycle carbon and energy budgets of biofuel production systems (both terrestrial and aquatic) to be determined. This research should include a forecasting element to take into account likely future technologies and future economic and policy conditions, so that robust models can be developed. Because biofuel systems that compete with food production are unlikely to be favoured, there should be empirical research into alternative systems, such as the ability of diverse grasslands or mixed biomass crops to generate sustainable high yields with minimal inputs, while simultaneously delivering other ecosystem service benefits.

C4 Fibre

The supply of fibres from plants and animals for the production of woven materials.

General significance

The provision of fibre has historically been a highly important ecosystem service to Europe. The wealth of many parts of Europe stems from production of materials and products based on wool, linen, cotton and silk. Although much of the fibre used in these manufacturing centres was initially produced locally, the trend has been towards the use of imported fibres, and most textiles consumed in the EU are now manufactured outside the EU. Historically, the wool industry was of principal importance in establishing Western Europe as a centre of manufacturing and export, but wool production is now a minor activity in Europe because of competition from synthetic fibres and imports from Australia and New Zealand. Sheep grazing does, however, remain a substantial activity, particularly in upland and marginal agricultural areas, providing subsidised incomes for rural areas, and supporting relatively low input pasture land. Sheep husbandry requires the use of topical pesticide applications with consequences for local water systems, but recent EU regulations have tightened controls on use of several of these.

Plant fibres have been produced for textile and binding applications for many years. Flax and hemp were major European crops with associated industries for the production of linen and rope. These industries, along with the associated agricultural production, were lost largely in the early twentieth century because of competition from imported cotton. Bast fibre textiles have largely been replaced by cotton, and ropes are now mostly made with more durable synthetic fibres. A small-scale industry based on locally produced flax remains in Belgium and northern France, producing high-quality linen for the fashion industry. In recent years, attempts have been made to re-establish a bast fibre industry in Europe. Bast fibres from flax and hemp have mechanical and insulation properties competitive with synthetic fibres. The automotive industry has started to adopt plant-fibre-based composites for low-grade applications such as interior panelling in cars. However, there are substantial problems in the uptake of plant fibres for composite applications, mostly related to reliability in raw material quality and supply (deJong et al. 1999). To extract bast fibres, the plant stems need to undergo a process of partial degradation, called retting. Historically, this was achieved by submerging plants in large tanks and ponds allowing partial anaerobic digestion to occur, but the adverse effects on the environment of this process (and the appalling smell) led to it being abandoned in favour of dew retting, whereby the cut crop is left to partly rot in the field. The unpredictability of dew retting leads to large losses of fibre and highly inconsistent quality. Until these problems are overcome, the widespread uptake of bast fibre crops in Europe seems unlikely.

Cotton is not a major crop for Europe although there is some production in southern countries. Cotton cultivation requires high inputs of freshwater and chemicals, particularly pesticides. The introduction of genetically modified cotton varieties expressing insecticidal *Bacillus thuringiensis* toxins has reduced quantities of pesticide sprayed on the crop, along with decreased carbon emissions and increased farmer profits (Quaim & de Janvry 2005).

The pulp and paper industry has a significant presence in Europe, using both recycled paper and forestry crops. Agro-foresty is a major activity in parts of northern Europe, as well as in more southerly areas such as Spain and Portugal where there are significant areas of eucalyptus production. Pulp production generally relies on rapidly growing monocultures, with relatively short rotation times. The pulping industry itself has historically been a substantial source of environmental pollution, particularly for water resources because of the need for harsh chemical treatment to release and bleach the fibres. Substantial improvements in emissions from pulp mills have been achieved, particularly in Sweden in response to regulatory constraints (Environmental Performance, Regulations and Technologies in the Pulp and Paper Industry 2006 EKONKO Inc.), which tends to stimulate process innovations. Genetic modification has led to some trees with altered lignin structures that are easier to pulp, which may decrease the chemical requirements for pulping in the future (Pilate et al. 2002).

Role of biodiversity

Commercial production of plant fibres is mostly confined to the pulp and paper industry in Europe, with most raw pulp being produced from highly managed monocultures of fast-growing pine and eucalypts. Trees planted for pulp are grown at relatively high densities, resulting in limited scope for biodiversity. Such large-scale monocultures are vulnerable to runaway pathogen attack, of the sort that recently devastated pine forests in western Canada (Mock et al. 2007) (compare with section B2). Biodiverse cropping systems may prove of value in terms in ensuring robust future productivity. Textile fibre crops currently account for very minor areas of arable land. Wool production is generally a low-intensity activity on semi-managed pasture lands with the potential to support considerable biodiversity.

Ecosystems involved

Fibre production in Europe is currently largely confined to forestry plantations on sub-optimal agricultural land or in areas supporting boreal forest. Wool production is generally confined to marginal farming areas in Europe such as upland pastures.

European concerns

Forest products represent a major component in the economies of the Nordic countries and Baltic states. These countries invest heavily in research to maintain their international competitive position, as well as to increase their environmental sustainability, and this should be encouraged and supported. Wool production is not an economically advantageous occupation currently in Europe, owing to competition from Australia and New Zealand in particular, and may not survive without subsidies. Bast fibre crops such as hemp and flax are attractive as they require relatively low inputs in terms of agrichemicals, but seem unlikely to become major crops without additional research and support.

Policy implications

The production of fibres for textiles is a very limited activity in Europe at present and this is unlikely to change in the current globalised economy owing to competition with other regions producing cotton and wool. Greater awareness of sustainability and the desire for localised rural production could change this in the coming years. The paper industry is a major consumer of freshwater and a major source of environmental pollution. Western societies continue to be major consumers of paper, and policy leading to reductions in paper consumption in EU will improve environmental sustainability.

Research needs

The drive toward greater environmental sustainability requires us to consider how to obtain maximum utility from agricultural products, while minimising impacts on the environment and biodiversity. An important aspect of this will be the development of integrated bio-refineries that ensure maximum value is extracted from plant products. It may be worth re-evaluating crops such as hemp that grow well with minimal inputs and produce a range of potentially useful materials including oil and protein from seed, as well as bast fibres from stems, with residual biomass perhaps serving as biofuels. Replacing man-made fibres with plant fibres in various industrial contexts appears desirable, but careful life-cycle analyses should be undertaken to confirm this. Improving the recovery of bast fibres from plant stems will be important in improving fibre raw material quality to enable uptake of plant fibres into industrial applications. Reducing the chemical inputs necessary for paper production, as well as improving the capture and recycling of these inputs, will help improve the sustainability of the pulp and paper industries. The consumption of paper per capita in Europe is high and research into reducing this would be beneficial.

C5 Biochemicals

Materials derived from nature as feedstocks in transformation to medicines, food additives, etc.

General significance

Biochemicals encompass a broad range of chemicals of high value, for example metabolites, pharmaceuticals, nutraceuticals, crop protection chemicals, cosmetics and other natural products for industrial use (for example enzymes, gums, essential oils, resins, dyes, waxes) and as a basis for biomimetics that may become increasingly important in nanotechnology applications. The diverse industrial applications associated with bioprospecting are discussed in detail in chapter 10 of the Millennium Ecosystems Assessment.

Some of the best-characterised examples are pharmaceuticals. It has been estimated that of the top 150 prescription drugs used in the USA, 118 originate from natural sources (74% from plants, 18% from fungi, 5% from bacteria, 3% from vertebrates) (Ecological Society of America, www.actionbioscience.org). In addition to these high-value biochemical products, there is an important related consideration in the use of biomass for chemical feedstocks in addition to bioenergy (Royal Society report 'Sustainable biofuels: prospects and challenges', chapter 3, January 2008) where development of integrated biorefineries will generate the building blocks (platform chemicals) for industrial chemistry. Some of these products may be regarded as biochemicals. A report from the US Environmental Protection Agency (Bioengineering for pollution prevention through development of biobased energy and materials; State of the science report, September 2007) concludes that economically competitive products (compared with oil-derived) are within reach, for example for celluloses, proteins, polylactides, plant oil-based plastics and polyhydroxyalkanoates. The high-value products may make use of biomass economically viable, which could become a significant land-use issue.

Role of biodiversity

Biodiversity is the fundamental resource for bioprospecting, but it is rarely possible to predict which species or ecosystem will become an important source. A wide variety of species – microbial, plant and animal – have been a valuable source of biochemicals but the achievements so far are assumed to be only a very small proportion of what could be possible by more systematic screening. The impact of the current global decline in biodiversity on the discovery of novel biochemicals and applications is probably grossly underestimated because of a general lack of recognition of the potentially commercially important species.

This use to produce biochemicals might itself have a negative impact on biodiversity if over-harvesting removes a high proportion of the species – it is necessary to protect against this by agreeing harvesting protocols on a case-by-case basis. More problematically, biodiversity loss in consequence of relatively low-value activities such as indiscriminate logging may compromise the future high-value activities (as yet undiscovered) associated with the search for novel biochemicals and chemicals.

Ecosystems involved

All ecosystems are potential sources of biochemicals:– there are numerous examples from the oceans and shoreline, freshwater systems, forests, grasslands and agricultural land. Although species-rich environments such as tropical forests have often been assumed to supply the most products, there are many examples associated with European habitats. However, the problem of the general lack of a robust and reliable measure to assess the commercial or other value of an ecosystem is compounded by the expectation that most biochemical resources have yet to be discovered and exploited. Microbes seem likely to be especially rich in undiscovered metabolic capacities, and the complexity of soil ecosystems means that there is likely to be great potential in searching for novel biochemicals there.

European concerns/context

Because of the general lack of understanding about what controls biochemical production and about likely future sources of new agents (some which could satisfy currently unimagined applications), it may be assumed that the issues for biochemicals are broadly related to the issues for primary production. In the context of European competitiveness, however, there is also need to consider the issues for supporting European companies in their activities to identify and use biochemicals obtained from ecosystems in other countries. Thus, broadly there will be need for EU initiatives to support public–private partnerships with developing countries, with consideration of the options for protecting intellectual property and benefit sharing. There is a potential role for the European Commission in supporting pre-competitive research by helping to develop and make accessible integrated databases of the current biochemical resources as a basis for new discovery in the diverse industry sectors. Although there is a very large resource, it is assumed, to be tapped in the various natural species, there are also specific examples where genetic modification may add value. However, the EU is currently a difficult environment for this work on genetic modification.

Policy implications

The activities to identify new sources of established biochemicals/chemicals and novel biochemicals/chemicals are anticipated to increase. New high-value industries may be created. Advances in the fundamental science of genomics can be expected to be applied to enhance productivity of natural processes. It is important for EU innovation policy to capitalise on these broad opportunities. It is important that issues within the Convention on Biological Diversity relating to research and development of novel compounds are resolved.

Research needs

There is a major need in many industrial sectors for new programmes to screen natural products. In the pharmaceutical sector, there had been a move away from natural product screening on the assumption that genomics research would provide future targets for combinatorial chemistry-based approaches. A new mood of realism will see a return to screening natural products (especially if there is the prospect that yields/attributes can then be optimised using genomics-based techniques). For example, the need for companies to develop new approaches to tackling antibiotic resistance will likely include new natural product screening programmes (Royal Society symposium, March 2008, report In Press). As in other ecosystem assessment areas, there is a need to develop new research methodologies to map and value future options: this is particularly difficult in this area because of the magnitude of the future unforeseen applications when compared with present achievements.

C6 Genetic resources

Provision of genes and genetic material for animal and plant breeding and for biotechnology.

General significance

Current rates of extinction (both at local and global levels) make the continued availability of this provision from natural systems potentially a concern, especially in poorly documented ecosystems (soil, sea). Extinction rates within the EU appear to remain low, although data from poorly studied systems (for example soils, marine environments) are too patchy to make clear statements. Genebanks are better developed in the EU than elsewhere but have limited capacity to conserve the range of genetic diversity within populations.

As discussed elsewhere, genetic diversity of crops decreases susceptibility to pests and climate variation (Ewel 1986; Altieri 1990; Zhu et al. 2000). Especially in low-input systems, locally adapted varieties often produce higher yield or are more resistant to pests than varieties bred for high performance under optimal conditions (Joshi et al. 2001). In agriculture, the diversity of genetic resources comprises the traditional resources (wild types and the older domesticated landraces) together with modern cultivars. Genetic resources will be increasingly important in support of improved breeding programmes, for example for crop plants, farm animals, fisheries – with wide range of objectives for increasing yield, resistance to disease, nutritional value, adaptation to local environment and to climate change. The advances in genomics research are opening up a new era in breeding, where the linkage of genes to traits (marker-assisted selection) provides a more efficient and predictable route to conventional breeding programmes. There are also increasing opportunities for genetic modification – for example where a desirable characteristic may only be available by using an unrelated species.

Genetic resources are also important for other purposes – for example in support of new activities to identify and optimise the production of important biochemicals (section C5).

Role of biodiversity

This is a service for which biodiversity is of central importance, because genetic diversity is inevitably lost when biodiversity declines. In so far as the delivery of genetic diversity can be viewed as a service in itself, therefore, biodiversity is fundamental to it. The greatest focus on genetic diversity as a service is in the protection of gene pools for agriculture. The Food and Agriculture Organization of the United Nations (FAO) has done much significant work at the global level to support characterisation of genetic resources in the food crop, livestock, fisheries and forestry sectors, but quantifiable data on trend analysis in genetic resources are very limited and have been collected for relatively brief periods. There are now numerous initiatives to collect, conserve, study and manage genetic resources *in situ* (for example growing crops) and *ex situ* (for example seed and DNA banks) worldwide, including most EU countries. New techniques using molecular markers are providing new precision in characterising biodiversity (at the level of molecular systematics and taxonomy) and the genetic diversity within collections – a significant aid to developing management strategy to identify gaps and redundancy (Fears 2007).

Ecosystems involved

All ecosystems are important. Agricultural biodiversity can be considered to have a special status because of previous human efforts to improve varieties, hence the specific focus of the International Treaty on Plant Genetics Resources to conserve the resources for food and agriculture. The replacement of landraces by high-yielding food crop varieties, taken together with other changes in agricultural practice (for example the collectivisation of large farms in Eastern Europe), has accelerated the erosion of genetic variation in cultivated material. The loss of genetic diversity associated with more intensive agriculture may also have deleterious impact on the non-domesticated plants and animals (and micro-organisms) in the ecosystem. A decline in crop genetic diversity has consequences for their genetic vulnerability and their plasticity, for example, to respond to biotic and abiotic stress. However, much more research using molecular marker-based technologies is now needed to monitor the change in genetic diversity and help quantify the challenges for sustainable agriculture. Such research is now getting started at the EU level (for example the European Commission-funded Crop Genetic Diversity Project, www.niab.com/gediflux).

European concerns/context

There has been a resurgence of EU interest in this area (for example the joint European Commission–industry Technology Platforms on Plants for the Future and on Animal Health), partly in consequence of the 2004 EASAC report *Genomics and crop plant sciences in Europe*. However, the mechanisms linking laboratory to field are still poor. There is need to build better relationships between fundamental science and breeding, because both commercial and academic expertise has been lost from the EU in plant sciences and in conventional breeding programmes in consequence of the deteriorating environment for genetically modified products. There is need to grow the skills for curation and use of gene and seed banks within the EU and the appropriate sharing of their information and benefits. In addition, the EU must explore the opportunities for capitalising on global genetic resources, both for local European applications and to support technology transfer to developing countries.

Policy implications

Because the bulk of genetic diversity exists in natural and semi-natural ecosystems, there is need to ensure that existing policies on biodiversity loss and on protection of habitats (for example Natura 2000) are implemented, and that ecosystems that currently lack protection, notably soil and much of the marine environment, are given proper protection.

Access to genetic resources is governed by the Convention on Biological Diversity and by the International Treaty on Plant Genetic Resources for Food and Agriculture. The latter has significant potential on a multilateral basis to support plant breeding research in Europe, but it is ambiguous about what specific genetic resources would be patentable. There is need for further debate on alternative options for treating genetic resources as public goods, for example the option of open-source licensing methodology for sharing information, with patent protection focused on end products.

There is a general difficulty in valuing genetic resources as a basis for breeding improved varieties because of uncertainties in the cost required to validate proof of concept and in the likelihood of reduction to practice. Thus, there is need to build stronger linkages between the technical, regulatory, commercial communities and policy-makers.

Research needs

The role of genetic diversity in determining the attributes of populations and ecosystems is an important area of fundamental research: we need to establish the extent to which genetic richness confers attributes such as stability and resilience.

There is a large amount of research to be completed to address currently identified priorities in genome sequencing, characterisation of key gene functions at the molecular level and as determinants of physiology, for use as resources in structured breeding programmes. The EASAC report (2004) provides detailed discussion of some of the EU priorities (augmented by Fears (2007) for the global level). In addition to research on the determinants of food production, research is required to support new crop/biomass applications for bioenergy and chemical feedstocks.

D. Cultural services

The services listed under this heading by the Millennium Ecosystem Assessment are best viewed as falling into two groups:

(1) spiritual, religious, aesthetic, inspirational and sense of place;

(2) recreation, ecotourism, cultural heritage and educational.

General significance

All these services have a large element of non-use values, especially those in the first group to which economic value is hard to apply. Those in the second group are more amenable to traditional valuation approaches. Although all societies value the spiritual and aesthetic 'services' that ecosystems provide, these may have different significance in affluent, stable and democratic societies (Pretty et al. 2005). Nevertheless biodiversity plays an important role in fostering a sense of place in all European societies and has considerable intrinsic cultural value (Moore 2007).

Evidence for the importance of these services to citizens of the EU can be found in the scale of membership of conservation-oriented organisations. The largest membership organisation in the EU is the National Trust in the UK, with 3.4 million members. Other large societies in the UK include the Royal Society for the Protection of Birds (more than one million members) and the Royal Society for Nature Conservation (670,000), whereas in Germany the Naturshutzbund (NABU) has 450,000 members.

Cultural services are of unusually high importance in Europe because of the high value placed by Europeans on recreation, tourism and ecotourism. Stark evidence of the relative importance of these services compared with traditional forms of land use was given by the 2001 foot and mouth disease epidemic in the UK, which closed large areas of the uplands to tourism; one estimate of the economic impact was that gross domestic product fell by £3.8 billion during 2001 and 2002 as a result of the epidemic, of which 86% was due to losses in tourism.

Most ecosystem-related tourism is protective of biodiversity; indeed the desire to see particular species may be the rationale for the visit in many cases. In contrast, some recreational uses of ecosystems are actually or potentially damaging. Shooting of migratory birds is the most blatant of these and is the cause of conflict between the EU and certain Member States in southern Europe, but the management of land for game birds is also viewed by some as destructive of biodiversity because it typically involves suppression of predatory species. Golf courses are a substantial user of land in some parts of the EU; traditionally, golf course management was a low-intensity activity, but modern approaches are often associated with low biodiversity and high water and agrochemical use, making them potentially or actually damaging.

Role of biodiversity

The role of biodiversity varies greatly among these services but is likely to be particularly large for ecotourism and educational uses of ecosystems. However, in many cases biodiversity may not be the typical identifier of the value being placed on the ecosystem, but nevertheless underlies the character recognised by the visitor. Typical landscapes in different parts of Europe are in part identifiable by the organisms, especially trees, growing there. Schröter et al. (2005) predicted that several typical tree species of the Mediterranean region are likely to decline as a result of the impact of climate change, including cork oak (*Quercus suber*), holm oak (*Q. ilex*), aleppo pine (*Pinus halepensis*) and maritime pine (*P. pinaster*). Some key cultural sites are protected by ecosystems that are vulnerable to climate change: for example, vegetation changes in response to sea level rise will undermine the halophytic ecosystems surrounding the lagoon of Venice. These changes would affect the sense of place and cultural identity of the inhabitants, traditional forms of land use and the tourism sector. Phillips (1998) also argues that several Europe-wide studies have confirmed the many conservation and environmental values associated with such traditional landscapes, and that they can also act as models for the sustainable use of natural resources.

Many cultural services are associated with urban areas, especially those with very long histories of human occupation; in these the role of biodiversity is likely to be less important. However, there is good evidence that biodiversity in urban areas plays a positive role in promoting human well-being. For example, Fuller et al. (2007) have shown that the psychological benefits of green space in Sheffield increase with biodiversity, whereas a green view from a window increases job satisfaction and reduces job stress (Shin 2007). Green spaces also promote health by encouraging exercise and have obvious educational benefits.

Ecosystems involved

Cultural services based on biodiversity are most strongly associated with less intensively managed areas, where semi-natural biotopes dominate. These large areas may provide both tranquil environments and a sense of wilderness. Low-input agricultural systems are also likely to support cultural services, with many local traditions based on the management of land and its associated biological resources.

Policy implications

Although separated here, cultural services provide a coherent challenge to policy, in that preferences expressed in economic terms (for example tourism) are based on aesthetic and other perceptions. Policy (especially agricultural policy) needs to be aimed at developing sustainable land-use practices across the EU, to deliver cultural, provisioning and regulatory services effectively and with minimal cost. Maintenance of diverse ecosystems for cultural reasons can allow provision of a wide range of other services without economic intervention. However, there will frequently be actual or potential conflicts arising when different cultural traditions meet. Good examples of these conflicts include the shooting of migratory birds by hunters in Mediterranean countries conflicting with the desire of many northern Europeans to conserve (and view) these birds; the protection of geese by conservation bodies in western Scotland conflicting with farmers' needs to reserve grazing for livestock rather than the geese; and the perceived need by managers of game-bird estates in Scotland and northern England to control predators such as hen harriers (*Circus cyaneus*) that prey on young grouse but which are protected.

Research needs

Progress in understanding the role of cultural services will depend on new interdisciplinary working methods bringing together natural and social scientists, to allow more appropriate economic models and effective measurements of interactions between people and natural systems.

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Annex 2 Previous EASAC work on biodiversity

Since its inception, EASAC has produced eight reports, and a series of briefing papers, on a range of scientific topics. Each of these has had a specific relevance to policy development in the European institutions of governance, the EU Commission, Parliament, Council and the Economic and Social Committee. However, the governments and public at large within Member States are also seen as audiences for EASAC's reports.

In the autumn of 2004, the European Parliament Environment Committee commissioned EASAC to prepare a briefing on indicators of biodiversity. It was the Committee's concern that the EU Sustainability report, prepared by the European Commission, had so far failed to provide information on trends in biodiversity in the EU. Parliamentarians were trying to understand whether there were suitable indicators available and, if so, what factors were impeding their use.

In a follow-up visit to the European Parliament Environment Committee Secretariat and the Commission's DG Environment, it emerged that, although the concept of ecosystem services was recognised as a powerful idea, such thinking was not in general currency within the Commission and, indeed, was subject to considerable suspicion from Commission economists. The EASAC Secretariat agreed to consider how EASAC might respond to these concerns.

In May 2006, the Royal Society's Science Policy environment team met with the EASAC Secretariat to discuss the potential for EASAC to undertake a project on ecosystem goods and services. The intention was to investigate whether EASAC could look at ways to take the Millennium Ecosystem Assessment framework forward in a European context given the recent developments in EU policy, and in particular the emphasis of EU economic and social policy over broader sustainable development, environment and biodiversity policy. EASAC Council approved a proposal for this work in June 2006.

Annex 3 Working Group members and expert consultation

This report was prepared by a Working Group of experts, acting in an individual capacity, and was reviewed and approved by EASAC Council.

Members of the Working Group

Alastair Fitter (Chairman)	University of York, UK
Erwin Bulte	Tilburg University, the Netherlands
Thomas Elmqvist	Stockholm University, Sweden
Andrea Rinaldo	University of Padua, Italy; and Ecole Polytechnique Federale Lausanne, Switzerland
Heikki Setälä	University of Helsinki, Finland
Susanna Stoll-Kleemann	University of Greifswald, Germany
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John Murlis (Secretary)	EASAC, UK

During the course of this work, many experts were consulted on the content of Annex 1, and we are pleased to acknowledge their contribution. Special thanks go to Marian Potschin, Roy Haines Young and colleagues at the University of Nottingham for a major contribution in preparing Annex 1. Charles Perrings also provided valuable input to the main report.

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