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ECOSYSTEMS

A Qualitative Ecosystem Assessment for Different Shrublands in Western Europe under Impact of Climate Change

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ABSTRACT

Climate change may affect the dynamics of ecosystems and the goods and services they provide. To investigate the consequences of warming and drought for the goods and services provided by different shrublands in various western European countries, an assessment was carried out using results of field manipulation experiments of the CLIMOOR and VULCAN projects. Goods and services of these shrublands mainly encompass biodiversity, various forms of recreation, conservation of culturally and historically important landscapes, groundwater as a drinking water source, and carbon sequestration. Warming of dry lowland heathlands in The Netherlands and Denmark increases nutrient availability, which may lead to grass encroachment reducing biodiversity and decreasing recreational values. Drought may reduce the chances of grass encroachment but increase the chances of disturbances to heather vegetation. Similarly, warming increases and drought decreases the chances of nitrate pollution to the groundwater, which is often used as a drinking water source. Warming of the upland heathland in the UK increases its productivity, which might enable higher grazing densities leading to improved agricultural production. However, complex interactions between heather and invading species may be affected. Furthermore, nitrate production is increased, which may lead to groundwater pollution. Under drought conditions, productivity decreases and agricultural production capacity drops. In the Mediterranean shrubland in Spain, both warming and drought led to a shift in the species composition of seedlings and recruitment, which might lead to a change in the plant community and a reduction in biodiversity. In the drought treatment, a decreasing soil carbon content may lead to a loss of biodiversity, recreational possibilities, and an increased threat of wildfires and erosion.

Key words: climate change; warming; drought; ecosystem assessment; heathland; shrubland.

INTRODUCTION

Although there is still much debate on the issue of global warming, there is less discussion on the need to anticipate the consequences of climate changes for humanity. Climatic factors, such as temperature

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and precipitation, are important parts of the environmental conditions that determine the composition and dynamics of ecosystems. Many past and ongoing research projects have focused on the potential effects of changes in the climatic parameters on the functioning of various ecosystems (Rustad and others 2001). Shrublands are typical ecosystems in Europe. Most are man-made and require some sort of management to preserve them. Furthermore, they usually have a low economic value but a high natural value. Often these shrublands suffer from lack of management, polluting aerial deposition, overgrazing, excessive wildfires, or size reduction or fragmentation due to different land uses. Climate change may add to these threats and make these ecosystems even more vulnerable. In the European Union funded research projects CLIMOOR (climate-driven changes in the functioning of heath and moorland ecosystems) and VULCAN (vulnerability assessment of shrubland ecosystems in Europe under climatic changes), the climate of several different western European shrublands has been manipulated at the field scale by applying nighttime warming or a summer drought period for several years (Beier and others 2004). In these experiments changes were observed in the soil, the vegetation, and the nutrients (Emmett and others 2004; Gorissen and others 2004; Llorens and others 2004; Peñuelas and others 2004; Schmidt and others 2004).

Ecosystems fulfill important human needs by providing goods and services, such as food, clean water, timber, protection (against, for example floods), cultural values, recreational opportunities, and so on. If changes in the climate affect the ecosystem, these goods and services are likely to be affected as well. In this article we qualitatively assess the consequences of climate change on the goods and services provided by European shrublands using the results from the field-scale experiments CLIMOOR and VULCAN. The goods and services provided by the shrubland ecosystems are summarized and the effects of warming and drought observed in the experiments are used to evaluate how such changes might affect these goods and services.

Materials and Methods

Shrublands and Experiments Used in the Study

The manipulations within CLIMOOR were carried out at four different European shrublands: Mols, Denmark (DK): lowland dry heathland; Oldebroek, The Netherlands (NL): lowland dry heathland; Clocaenog, United Kingdom (UK): upland heathland; and Garraf in NE Spain (ES): Mediterranean shrubland, originating from forest and kept as shrubland mainly by recurrent wildfires (Table 1, Beier and others 2004). These shrubland ecosystems were chosen because they represent an important natural resource within their regions and are known to be very sensitive to changes in environmental conditions (Heil and Bobbink 1993). All sites were dominated by shrubs (greater than 50%) of which a major component was from the ericaceous family. The sites in DK, UK, and NL were dominated by *Calluna vulgaris* and *Deschampsia flexuosa* to various degrees. The Spanish site was dominated by *Erica multiflora* and *Globularia alypum*. Furthermore, the sites differed with respect to temperature (being higher southward), precipitation (increasing westward), and nitrogen deposition (Table 1). N deposition is believed to be a very important factor interacting with climate variables, as its effects upon the shrublands are brought about through temperature- and moisture-dependent processes.

In the four different shrublands the climate was manipulated in nine 20-m^2 plots using three replicates for each of the two manipulation treatments and three control plots. The treatments consisted of (Beier and others 2004):

1. nighttime warming—the study plots were covered at night by reflective aluminum curtains to reduce the nightly heat radiation; the warming treatment was applied for two years starting in March 1999. The temperature of the soil and plants increased on the order of 0.5–2°C.
2. drought—the study plots were covered with transparent plastic curtains during rainfalls to simulate an extended drought period for about two months in the growing season.
3. control—the treatment effects were evaluated by comparison to untreated control plots.

In the plots the treatments and potential artifacts were evaluated by measurements of soil and air temperature, water input by precipitation, wind speed, and radiation. The effects of the treatments on soil and plant processes and carbon and nitrogen dynamics were monitored.

Goods and Services

An overview of the goods and services provided by the shrubland sites in this study is given in Table 2. Most heathlands have at some time provided agricultural goods and services, but nowadays the significance of this is reduced. The agricultural goods most lowland heathlands provided were the reason

Table 1. Main Site Characteristics for CLIMOOR Sites

Site name Country	Mols DK	Clocaenog UK	Oldebroek NL	Garraf ES
Location	**56°23'N**	**53°03'N**	**52°24'N**	**41°18'N**
	10°57'E	3°28'W	5°55'E	1°49'E
Altitude (*m*)	58	490	25	210
Air temperature (°C)				
Annual average	9.4	8.2	10.1	15.1
January	1.6	4.3	2.0	7.4
July	18.1	12.4	17.8	22.5
Precipitation (mm yr^{-1})				
1998–2000	758	1741	1042	455
Soil	Sandy podzol	Peaty podzol	Sandy podzol	Petrocalcic calcixerepts
Vegetation	*Calluna vulgaris-Deschampsia flexuosa*	*Calluna vulgaris Deschampsia flexuosa Vaccinium myrtillus Empetrum nigrum*	*Calluna vulgaris Deschampsia flexuosa-Molinia caerulea*	*Erica multiflora-Globularia alypum*
Plant cover	100	100	95	57
Aboveground				
C stock (g C m^{-2})	499	1790	584	275
N stock (g N m^{-2})	9	34	10	5
C:N ratio	55	53	58	60
Belowground (0–45 cm)				
C stock (g C m^{-2})	3760	14800	6835	3684
N stock (g N m^{-2})	275	390	283	354
Organic soil C:N ratio	18.5	37.4	22.5	not determined
N input (kg N $ha^{-1}yr^{-1}$) 1998–2000	25–30	20–25	30–40	10–15

Table 2. Goods and Services Provided by Different European Shrublands

Country	DK	UK	NL	ES
Food and water	Drinking water	Drinking water Grazing	Drinking water	
Biodiversity	Nature conservation	Nature conservation	Nature conservation	Nature conservation
Carbon storage		Soil carbon conservation		
Tourism/recreation	Cultural landscape preservation Recreation	Cultural landscape preservation Recreation Hunting	Cultural landscape preservation Recreation	Cultural landscape preservation Recreation Hunting Soil conservation
Other	Military training grounds		Military training grounds	Military training grounds

for their creation, namely nutrients and organic matter to improve arable soils. This was achieved by herding sheep and other cattle on the heathlands and collecting their waste products at night in stables, by mowing the vegetation, and by sod-cutting. Animal waste products, vegetative remains, and sods were applied to the arable land (Webb 1998). As a result, the heathlands became impoverished and developed their typical vegetation (Specht 1979). As artificial fertilizers became available, heathland as a source of nutrients became superfluous and, as a result, the area of lowland heathlands greatly diminished. Mediterranean shrublands are not part of an agricultural system, but they can originate from agricultural land, as is the case in the Garraf area. The terraces present here are the visible remains of this former function. This former agricultural function was the reason for the removal of the original vegetation in the past. However, similar to the lowland heathland, the Mediterranean shrublands do not play any significant agricultural role today. Only many upland heathlands, comparable to the site in the UK, still have an agricultural function. They are used for free-range grazing, mainly by sheep. This contributes to the agricultural production, but it is also important for the local economic conditions of these remote rural areas. Therefore, the government supports these activities with subsidies because the economic viability of these activities is low (Thompson and others 1995).

Clearly, despite these former agricultural functions, shrublands have now become areas of limited economical interest. However, their natural value are now more appreciated (Gimingham 1992). In The Netherlands, for example, a working group on the future of heathlands there initiated by The Netherlands government (Anonymous 1988) concluded that heathlands in this country constitute a diverse and nationally and internationally precious community. Furthermore, they form the most important nutrient-poor component of the landscape of higher sandy soils and are an essential ecological link in the landscape of higher sandy soils for the conservation and distribution of a number of species (Anonymous 1988). Cryptogams form an important part of the nature conservation value of the heathland ecosystem (Berdowski 1993; Thompson and others 1995; Britton and others 2000). Upland heathlands are also particularly important for birds (Thompson and others 1995). Mediterranean shrublands are considered biodiversity hotspots (Myers and others 2000; Pineda and others 2002). In the Iberian Peninsula they are particularly rich in plant species diversity, including a large number of endemisms. In addition, birds, reptilians, and amphibians are well represented (Pineda and others 2002).

In addition to the natural values, these shrublands also contain cultural and historical values. This is in particular the case in the northern countries where heathlands form part of an old, once important agricultural system (Anonymous 1988; Webb 1998). Its cultural importance manifests itself, for example, in the existence of a traditional regional heather festival in The Netherlands (near the town of Ede) held during the flowering period of the heath.

Together with biodiversity conservation, recreation is at present probably the most important service in all heathlands considered. Heathlands are used for walking and cycling. Furthermore, this open landscape has its unique scenic quality (Anonymous 1988). The flowering heather has in this respect a particular esthetical quality. Another recreational service of shrublands is their use for sport shooting. This is especially the case in the UK and in Spain. In the UK upland heathlands have a role as hunting grounds for red deer (*Cervus elaphus*) and the red grouse (*Lagopus lagopus scoticus*) on so-called grouse moors (Gimingham and others 1979). This sport shooting is of considerable economic value (Macdonald and others 1995). The importance of shrublands as hunting areas in Spain is illustrated by the fact that the 10,000-ha Garraf nature reserve accommodates about 1200 hunters.

Today carbon storage has become an additional important issue in these ecosystems. With the low vegetation of this type of ecosystem, the main carbon pool is in the soil (Table 1). Shrubs usually produce a very slowly decomposing litter. The peat soil of the UK site contains a large store of carbon (Emmett and others 2004). The conservation of this C store is an environmental concern and, therefore, is a service of this type of ecosystem to society.

The vegetation cover also serves to protect the soil, minimizing soil erosion. This is especially important in the Mediterranean where precipitation can be very intense in spring and autumn. Furthermore, because of the minimal management activities and the relatively low deposition of elements, the groundwater below many of these shrublands is used for drinking water. Finally, heathlands in The Netherlands, Germany, and Denmark and shrublands in Spain are used as military training grounds. Of course, this use poses little specific demands on the ecosystem, apart from a certain amount of variety in the landscape and sufficient open space for maneuverings. However, the demands for space in, for example, The Netherlands are such that it is necessary to combine the use as military training grounds with other uses, such as nature reserve or recreation.

Preservation of these man-made ecosystems requires management, including such costly measures as grazing, sod-cutting, and burning. Thus, both revenues and costs are involved in maintaining these systems (Gimingham 1992).

Results

Effects of Experimental Climate Manipulations

The results of the first two years of the CLIMOOR warming and drought treatment experiments are reported in several publications (Emmett and others 2004; Gorissen and others 2004; Llorens and others 2004; Peñuelas and others 2004; Schmidt and others 2004). To assess the possible effects upon goods and services, we focus on the biological transformation processes of the vegetation and in the soil because these are mostly strongly temperature and moisture dependent. In oligotrophic ecosystems, such as these heathlands, the changes in nutrient dynamics and nutrient availability deserve primary attention. The organic matter dynamics are relevant as well, not only because of the C storage in the ecosystem but also because nutrients, such as N, can be fixed in organic compounds, reducing available-nutrient levels (Berendse 1994). Soil organic matter is also important for the soil characteristics, affecting, for example, its water content and its erodability. Furthermore, we consider the changes in species composition, flowering, and sensitivity to drought and temperature of the dominant plant species.

We consider observed changes for a period of two years because this is the length of the experiments to date. However, after more years of treatment the outcome may differ, for example, because the system reaches a new state of relative stability. Therefore, we have assessed changes and their implications only in a qualitative way.

The Netherlands (NL)

Warming Treatment. At the Dutch site in Oldebroek, plant primary productivity tended to increase (Peñuelas and others 2004). A slight decrease was found in foliar P content and an increase in foliar N:P ratio (Peñuelas and others 2004). Herbivory damage (by the heather beetle) tended to increase, whereas litterfall significantly decreased (Peñuelas and others 2004). There was a trend toward increased soil respiration rates (Emmett and others 2004). Significant increases in litter initial mass loss rates were observed; this effect was reduced with time (Emmett and others 2004). Nitrogen mineralization and nitrification rates in the soil were both significantly enhanced (Emmett and others 2004). Soil water responded with a strong increase in NO_3 concentrations below the rooting zone and with higher DON losses in seepage water (Schmidt and others 2004).

Drought Treatment. Drought reduced the rates of photosynthesis and transpiration (Llorens and others 2004). Herbivory increased, whereas flowering tended to decrease (Peñuelas and others 2004). The foliar P content of *Calluna vulgaris* decreased significantly and litterfall was also significantly decreased (Peñuelas and others 2004). There was a trend toward decreased litter mass loss rates in the early stages of decomposition; this effect was reduced with time (Emmett and others 2004). Soil respiration rates tended to decrease (Emmett and others 2004). Nitrogen mineralization and nitrification rates in the soil were both significantly decreased (Emmett and others 2004), and element fluxes in the soil solution were generally reduced (Schmidt and others 2004).

Denmark (DK)

Warming Treatment. The *Calluna* plants responded with a 25% reduction in short-term uptake of CO_2 (Gorissen and others 2004; Peñuelas and others 2004), whereas a smaller fraction of this CO_2 taken up was allocated to the soil (Gorissen and others 2004). Herbivory tended to increase whereas the foliar N content of *Calluna vulgaris* increased significantly, and the foliar P content of *Deschampsia flexuosa* decreased significantly, leading to a larger N:P ratio of the vegetation (Peñuelas and others 2004). Soil respiration increased, which was significant on several measurement occasions, and there was a trend for increased litter initial mass loss rates; this effect was reduced with time (Emmett and others 2004). There were significantly higher rates of nitrogen mineralization and nitrification beneath *D. flexuosa* plants relative to *C. vulgaris.* Differential effects of warming were observed beneath the two species (Emmett and others 2004). There was a significant increase in nitrate leaching from the organic layer in the first winter and DON losses in seepage water were also higher (Schmidt and others 2004).

Drought Treatment. Plants responded to drought by reducing photosynthetic and transpiration rates and lowering actual photochemical efficiency (Llorens and others 2004). The short-term uptake of CO_2 was reduced by 39% (Gorissen and others 2004; Peñuelas and others 2004), and a larger fraction of this CO_2 taken up was allocated to the stems, whereas the fractions in all other plant and soil compartments decreased (Gorissen and others 2004). Herbivory tended to increase, and the foliar P content of *Calluna vulgaris* decreased significantly (Peñuelas and others 2004). In the soil, there was a trend toward decreased litter initial mass loss rates; this effect was reduced with time (Emmett and others 2004). There were also decreased soil respiration rates; this was significant on several sampling occasions (Emmett and others 2004). There was a variable response in net N mineralization and nitrification to drought beneath the two species (Emmett and others 2004), whereas dissolved element fluxes in the soil solution were reduced (Schmidt and others 2004).

United Kingdom (UK)

Warming Treatment. Shoot-length growth and net primary productivity tended to be enhanced (Peñuelas and others 2004). Although the short-term uptake of CO_2 appeared unaffected, less of this CO_2 was allocated to the soil (Gorissen and others 2004). Herbivory damage was increased significantly, foliar P content decreased slightly, and the foliar N:P ratio increased (Peñuelas and others 2004). Litterfall tended to decrease (Peñuelas and others 2004). There was a trend toward increased soil respiration but no significant effect on litter mass loss rates (Emmett and others 2004). Leaching of nitrate from the organic layer was increased and DON losses in seepage water were also higher (Schmidt and others 2004).

Drought Treatment. Shoot-length growth and net primary productivity tended to decrease (Peñuelas and others 2004). Photosynthetic and transpiration rates were decreased as well (Llorens and others 2004). Although the short-term uptake of CO_2 tended to increase, less of this CO_2 was allocated to the soil (Gorissen and others 2004). Furthermore, there was a significant decrease in the flowering of *Calluna vulgaris,* while litterfall also tended to decrease (Peñuelas and others 2004). There was a trend toward decreased soil respiration; this was significant on several occasions (Emmett and others 2004). However, there was no significant effect on litter mass loss rate (Emmett and others 2004). Element fluxes in the soil solution were reduced (Schmidt and others 2004).

Spain (ES)

Warming Treatment. Although net primary productivity was unchanged in this treatment (Peñuelas and others 2004), other parameters showed different responses. While stem diameter growth of *Erica multiflora* increased, it decreased in the other dominating species, *Globularia alypum* (Peñuelas and others 2004). Stem diameter growth of both species was decreased in the summer–autumn period but increased in the winter–spring period (Peñuelas and others 2004). Short-term uptake of CO_2 was reduced by 25%, although a smaller fraction of the CO_2 uptake was allocated to the soil (Gorissen and others 2004; Peñuelas and others 2004). *Globularia alypum* showed a significant decrease in foliar P content, while there was an increase in the N:P ratio of the vegetation (Peñuelas and others 2004). A decrease in seedling diversity was observed, and seedling recruitment of the shrubs *Erica multiflora* and *Globularia alypum* decreased, while that of the half-shrubs *Fumana ericoides, F. thymifolia,* and *Coris montspelliensis* increased (Lloret and others 2004; Peñuelas and others 2004). Finally, there was a significant decrease in litter initial mass loss rates; this effect decreased with time (Emmett and others 2004).

Drought Treatment. Drought reduced plant primary productivity (Peñuelas and others 2004), dry mass of leaves and stems of *Erica multiflora* (Gorissen and others 2004), as well as the stem diameter growth for both dominant species (Peñuelas and others 2004), and rates of photosynthesis and transpiration (Llorens and others 2004). Short-term uptake of CO_2 by *Erica multiflora* was reduced by 96%, while this carbon was stored relatively more in the stems and less in the leaves (Gorissen and others 2004; Peñuelas and others 2004). Furthermore, *Erica multiflora* had a significant decrease in foliar P content, whereas that of *Globularia alypum* tended to increase; the N:P ratio of the vegetation tended to increase (Peñuelas and others 2004). The flowering of *Globularia alypum* was significantly decreased (Peñuelas and others 2004). A decrease in seedling diversity was observed, while the seedling recruitment shifted from shrubs to half-shrubs, as in the warming treatment (Lloret and others 2004; Peñuelas and others 2004). There was a trend toward decreased litter mass loss rates in the early stages of decomposition; this effect was reduced with time (Emmett and others 2004). Soil respiration rates tended to decrease as well (Emmett and others 2004).

Discussion

Consequences for the Ecosystems and Their Goods and Services

Warming. In all three northern sites there was an increase in primary production, decomposition, and nutrient cycling and increased nutrient availability. This may affect the oligotrophic nature of the heathland (Specht 1979). Heathlands in The Netherlands are considered P limited on poorer soils and N limited on richer soils (Diemont 1996). The heathland of the Dutch study site seems P limited considering the large amount of N released below the root zone in the warming experiment. This is in agreement with the soil type found here. The increases in available N and the decrease in P in the foliage indicate that P is also the limiting nutrient in the Danish and UK sites. Although there are no direct indications that in the warming treatment P has also become more available to the vegetation, the increase in N cycling makes it reasonable to expect that this has occurred.

Increases in nutrients are thought to aid in the encroachment of grasses into lowland heathlands because grasses have an advantage over heather under richer nutrient conditions (Heil and Aerts 1993; Diemont 1996). A closed canopy of heather is unpenetrable to grasses until gaps in the heather canopy occur, allowing grasses to profit from the better nutrient conditions (Heil and Aerts 1993; Alonso and Hartley 1998). Gaps may occur as a result of aging of the plants, which have a maximum age of about 40 years (Gimingham and others 1979), but also because heather dies as a result of drought, frost, or herbivory by the heather beetle (*Lochmaea suturalis*) (Diemont 1996). The faster-growing *Calluna vulgaris*—as a result of the extra nutrients—may make the occurrence of gaps more likely as it increases the sensitivity of the plant to drought, frost, and herbivory (Berdowski 1993; Diemont 1996; Riis–Nielsen 1997). Indeed, herbivory damage was increased in the warming treatment at both lowland sites (Peñuelas and others 2004). In addition, higher nutrient levels are known to negatively affect vegetative regeneration of the heather (that is, after cutting or possibly grazing) (Berdowski 1993). This means that, if nutrient availability increases as a result of global warming, grasslands may replace heathlands. This is considered a loss because of a decrease in biodiversity (Berdowski 1993), a decrease in attractiveness from a recreational point of view, and a loss of cultural historic values, as the heathland ecosystem is part of the old farming systems practiced for ages. As N mineralization and nitrification in the Danish site increased more beneath *Deschampsia flexuosa* than beneath *Calluna vulgaris* indicating an increased N availability, there is a positive feedback encouraging encroachment by grasses.

It is more difficult to predict the consequences of changes in C and nutrient dynamics on the upland heathland in the UK. In experiments with heather plants and grasses, Alonso and Hartley (1998) found that an increase of nutrients could stimulate the grasses in competition with the heather. Therefore, warming might negatively affect the heather ecosystem. On the other hand, increased productivity of the heathland would make more intensive grazing possible, thus contributing to agricultural production. Genney (2000) linked the competitiveness of *Calluna* and the grass *Nardus stricta* to the existence of ericaceous mycorrhiza, which would help the *Calluna*. High N inputs and defoliation (as a result of intensive grazing or possibly beetle infestations) can reduce the presence of mycorrhiza (Yesmin and others 1996; Hartley and Amos 1999), giving *Nardus* an advantage. Thus, a shift to grasslands as a result of warming is also possible in the upland heathland. This would be a negative development for the goods and services such as biodiversity, cultural and historical values, and recreation.

In the Spanish site the observed changes in shrub growth were not consistent and were difficult to interpret for the vegetation as a whole. However, the different responses of the two dominating species indicate that these two species are affected differently by warming. Even if these changes are small, they could lead to large shifts in species composition if their competitiveness is altered. The observed decrease in seedling diversity and the shift in the recruitment of shrubs to half-shrubs are a further indication that warming may induce a shift in the composition of the plant community. If the recruitment developments are representative of later stages of plant development, decreased biodiversity will be the result.

Because both carbon sequestration and carbon decomposition are increased by warming, the net carbon accumulation effect is uncertain. However, in the warmest site in Spain, primary production did not respond to warming, while soil respiration increased. So in this case C accumulation is negatively affected by an increase in temperature. Changes from heathland to grassland may result in substantial changes in carbon sequestration. Replacement of grasslands by shrublands is thought to lead to an increase in carbon sequestration and is therefore considered to be an important contribution to the carbon sink in the global carbon budget (Pacala and others 2001; Goodale and Davidson 2002). However, a comparison of pairs of southwestern USA shrubland and grassland sites, which were both grasslands 30 years or more ago, has shown that carbon does not always increase in the shrublands. In three cases with precipitation above about 600 mm year^{-1}, there was a reduction in soil carbon in the shrublands compared to the grasslands. This reduction increased with increasing precipitation, while it was not completely compensated by an increase in plant carbon (Goodale and Davidson 2002; Jackson and others 2002). In the three other, dry sites (mean annual precipitation about 300 mm year^{-1}), the shrublands gained carbon compared to the grasslands. However, this carbon gain was small compared to the assumed amount (Pacala and others 2001), and to the amount of carbon lost in the wetter sites. Assuming this relationship is also true for shrublands converting to grasslands, the precipitation of the Spanish site would imply little or no loss of carbon if replaced by grassland. Our other sites resemble the three wetter USA sites, although the precipitation of the UK site exceeds that of the wettest USA site by about two-thirds. In these cases, carbon sequestration would benefit from replacement of shrubs by grasses. However, the Bonn agreement indicates that C sinks should not be encouraged at the expense of other ecosystem services such as biodiversity.

More nitrate was found in the soil solution of the organic layer or in the soil water beneath the rooting zone in all northern sites experiencing warming. Thus pollution of ground or surface water with nitrate is more likely, and warming can be considered a threat to the use of groundwater for drinking water. DON in seepage water can also be a source of nitrate in the soil and, therefore, increased DON contributes to this threat. The possible use of this water is a relevant service of this ecosystem, because in many countries these shrublands are considered potential sources of clean water. However, this potential threat to the groundwater is strongly dependent on how long the increased nitrate leaching is sustained. Losses of nitrate from the rooting zone also mean an acidification of the soil. Acidified soil combined with the increased availability of N relative to P, as indicated by the increased foliar N:P ratio, may decrease biodiversity in heathlands (Bobbink and others 1998; Roem and Berendse 2000; Roem and others 2002).

Drought. The decreases in productivity and nutrient cycling observed in the drought treatment in the northern sites might shift plant community composition in the opposite direction from that of the warming treatment considered in the previous section (Heil and Aerts 1993; Diemont 1996; Riis–Nielsen 1997; Alonso and Hartley 1998). Thus, in the lowland heathlands heather would be better able to compete with the grasses, and in the upland heathland the grazing capacity would decrease and heather might be better able to compete with grasses here as well because of the lower nutrient levels. This would benefit biodiversity and recreational and cultural values of the ecosystems but agricultural goods in the upland heathland would diminish. However, the increased drought conditions and herbivory damage could be fatal for heather plants, creating gaps in the canopy and thus promoting invasion by grasses. Vulnerability to drought of *Calluna* in competition with bracken (*Pteridium aquilinum*) in UK heathlands increased with increasing nutrient levels (Gordon and others 1999). Therefore, it is far from certain that drought will always stimulate the heather. Despite the opposing nutrient cycling trends in the warming and the drought treatments, the foliar P content often decreased in both treatments (Peñuelas and others 2004). Apparently, the drought treatment decreased P availability more than it decreased primary productivity. The decreasing foliar P content is an indication that P becomes increasingly limited and, in the future, may diminish primary production even more. In the Spanish site, drought and warming pose similar risks to biodiversity because comparable changes in seedling diversity and recruitment occurred. The decrease in flowering observed in The Netherlands and the UK is an additional threat to the recreational value of the heathland, as the flowering heathland is a much-valued part of the landscape.

The strong decrease in plant productivity in the Spanish site means a reduced input of organic matter to the soil. This will lead to a decrease in soil organic matter content, although this effect may be mitigated by slower soil organic matter decomposition, implying a longer residence time. A decrease in the organic matter content of the mineral soil would decrease the water retention capacity of the soil. If the water content of the soil decreases, it decreases the productivity of the vegetation, further decreasing the organic matter input into the soil. The decreases in water input together with the decrease in soil water content discussed above increase the risks of fire and its effects. Wildfires are already common in Mediterranean shrublands, including the region of the Spanish site (Vilà and others 2001), and there are indications that their frequency has increased in the last decades as a result of climatic change (Piñol and others 1998). More frequent fires would contribute to a further reduction in the productivity of the vegetation and the organic matter content of the soil. Together these processes would aggravate the direct effects of drought and push the ecosystem toward a more arid type. The value of the ecosystem for hunting and other recreational functions may decrease and the amount of C bound by the ecosystem becomes smaller. Apart from increasing the fire hazard in these areas, increasing drought also will extend the area vulnerable to wildfires.

The decrease in nitrification observed in the Dutch site as well as the decrease in soil nitrate fluxes in all northern sites makes pollution of the groundwater with NO_3 less likely. Also, soil acidification is decreased.

Reductions of soil organic matter in the Spanish site may also diminish soil aggregate size and stability, and this, together with the decrease in vegetation cover, may reduce the infiltration of water into the soil and increase the importance of surface flow. This may lead to erosion of soil further deteriorating the hydrological characteristics of the soil (Imeson and others 1998; Lavee and others 1998). Because the Spanish site consists of terraces originating from its former use as a vineyard, erosion is probably a less immediate threat here than in similar sites without terraces.

Response Options

All shrubland ecosystems considered here require some sort of interference to prevail. In the Spanish site this interference takes the form of recurrent wildfires, whereas in the northern sites it involves the regular removal of nutrients and vegetation by measures such as grazing, sod-cutting, clipping, and burning. Presently, the increase in nitrogen deposition has made the regular removal of nutrients even more necessary. Because these types of management activities are generally very costly, many of the northern heathlands already suffer from insufficient management (Anonymous 1988; Gimingham 1992; Riis–Nielsen 1997).

It appears that the adverse effects of increased temperature on heathlands, such as the sites in The Netherlands, Denmark, and the UK, operate mostly through the increased availability of nutrients. As a consequence, intensification of the above-mentioned management activities could be used to counteract these climatic effects. There are, of course, certain limitations. In the first place, these measures are costly and the increased costs should still outweigh the benefits of the heathlands. In addition, more frequent management of the heathland ecosystem may disturb or damage animal or plant species to such an extent that they are no longer sustainable or can no longer provide the services for which they are valued (Macdonald and others 1995). This could seriously decrease the natural values, even resulting in these measures becoming counterproductive. Furthermore, Diemont (1996) concluded that in The Netherlands *Calluna* is nearing the verge of its area of distribution. It is possible that even if nutrient status is kept low, *Calluna* would not be able to cope with the changed climatic conditions in the long term. A similar situation may be the case in the Danish lowland heathland. The measures mentioned result in a more uniform ecosystem, especially through the synchronizing of the *Calluna* plants, creating plants of all the same age. This reduces the natural value of the ecosystem (Usher and Thompson 1993), but it is also counterproductive because aging *Calluna* plants are increasingly less able to regenerate by adventitious rooting (Macdonald and others 1995) or resprouting (Berdowski 1993). Therefore, as the vegetation ages it becomes increasingly dependent on intensive management for its regeneration (Riis–Nielsen 1997).

In the Mediterranean shrublands, prevention of wildfires contributes to the prevalence of this ecosystem. To offset the increased chance of wildfires, as a result of climatic changes such as drought, measures can be taken similar to those in the northern sites such as grazing, clipping, and prescribed burning. At present, this kind of management is not practiced because of the costs or the risks involved.

There are also possible measures that are external to the shrublands. Increasing the size of small shrubland patches can reduce nutrient inputs from the environment. Larger areas are also easier to manage, reducing costs. For example, small patches cannot be burned because of risks to the surroundings and free-range grazing is only possible if the area includes a drinking water source for the cattle. A general reduction of atmospheric pollution, especially of N compounds, is a policy that governments have pursued for years, but its success is limited. Especially in The Netherlands, the ecosystems suffer from an extremely large load of N, and, to improve the conditions for the heather, current deposition has to be reduced by half (Heil and Bobbink 1993). Reduction of atmospheric N deposition would also be the most obvious countermeasure to reduce pollution of groundwater with NO_3.

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