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Responses of Climate Change on Natural Terrestrial Ecosystems in Norway

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NINA

NORSK INSTITUTT FOR NATURFORSKNING

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Abstract

Holten, J.I. & Carey, P.D. 1992. Responses of climate change on natural terrestrial ecosystems in Norway. - NINA Forskningsrapport 29: 1-59.

This report discusses possible effects of climatic and hydrological changes on Norwegian terrestrial ecosystems. Norway is tentatively subdivided into four ecoclimatic sensitivity regions, based on Norwegian climatic and hydrological scenarios. The most sensitive region is suggested to be alpine ecosystems including mountain forests (region I). The ecologically most significant factor for the changes in region I is snow cover and hydrology. The flat river valley bottom region (region IV) is suggested to have the same sensitivity as region I. Melting of permafrost can lead to substantial changes in Svalbard's ecosystems. In the forest region (region II) Scots pine may be favoured on the expense of Norway spruce. Dutch elm disease may reduce or even eradicate most elm populations in region II. Natural and anthropogenic migration barriers will delay the invasion of temperate and oceanic plant species. One may expect enhanced biodiversity in the hemiboreal and southern boreal zone in South Norway, whereas Central Norway may have lowered biodiversity in the long run. From existing lists of rare and threatened plants, 12 species are suggested to be threatened (directly or indirectly) by climate change. A non-linear type of ecosystem changes is expected in most ecosystems, triggered by a higher frequency and intensity of extreme weather events. The assessment of critical rates and levels of climatic change and tolerance limits for species, will depend on much better knowledge on ecosystem dynamics and processes, especially demographic processes. The ecotonal boundary method is recommended both for research and monitoring. For the organizing of climate impact research and monitoring in terrestrial environments, the axis ICSU-IGBP-GCTE is recommended.

Key words: Ecoclimatic sensitivity - non-linear response - extreme events - gaps - demographic processes - ecotonal boundary method - GCTE.

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Holten, J.I. & Carey, P.D. 1992. Reaksjoner på klimaforandringer i naturlige terrestriske økosystemer i Norge. - NINA Forskningsrapport 29: 1-59.

Denne rapporten diskuterer mulig virkninger av klimatiske og hydrologiske endringer på norske landøkosystemer. Basert på norske scenarier for klima og hydrologi er landet forsøksvis inndelt i 4 økoklimatiske følsomhetsregioner. Den mest følsomme regionen er antatt å være fjelløkosystemer sammen med fjellskog (region I). Viktigste faktor for økologiske endringer i region I er endringer i snødekke og hydrologi. Flate elvesletter (region IV), antas å ha samme følsomhet som region I. Smelting av permafrost kan føre til store endringer i Svalbards økosystemer. I skogregionen (region II) kan furu bli favorisert på bekostning av gran. Almesyke (Dutch elm disease) kan redusere og knekke mange almebestander i region II. Naturlige og antropogene (fragmentering) spredningsbarrierer vil kraftig forsinke innvandring av sørlige og vestlige plantearter. Det forventes en økt biodiversitet i hemiboreal og sørboreal sone i Sør-Norge, mens Midt-Norge kan få senket biodiversitet på lengre sikt. Fra eksisterende lister over sjeldne og truete plantearter er 12 arter antatt å bli truet (direkte eller indirekte) av utrydding. En ikke-lineær utviklingstype er forventet i de fleste økosystemer utløst av en høyere frekvens og styrke av ekstreme værepisoder. Fastsettelse av kritiske hastigheter og grenser for klimaendringer og toleranse-grenser for arter, vil forutsette en mye større kunnskap om økosystemenes dynamikk og prosesser, spesielt demografiske prosesser. "Økoton-metoden" er anbefalt både innenfor forskning og overvåking. For organisering av virkningsstudier av klimaendringer og monitoring i terrestriske økosystemer er aksen ICSU-IGBP-GCTE anbefalt.

Emneord: økoklimatisk følsomhet - ikke-lineær respons - ekstreme værepisoder - åpninger (gaps) - økoton-metoden - GCTE.

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Contents

Preface

This project is Norway's contribution to IPCC's Supplementary Report on Natural Terrestrial Ecosystems (related to climate change). The project has been a co-operative venture between the United Kingdom, ITE (Institute of Terrestrial Ecology), and Norway, NINA (Norwegian Institute for Nature Research). The work would not have been possible without funding from the Directorate for Nature Management, Trondheim. I would like to acknowledge Dr. Peter Carey for his many original contributions to the report and for additional discussions. I would also like to thank Richard Binns for linguistic corrections.

Trondheim, January 1992

Jarle I. Holten
Project leader

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) has asked NINA, in a letter dated 26th September 1991, to contribute to a reassessment of the IPCC working group II (Impacts) report "Ecological impacts of climate change". It was requested that a report be prepared with the aims of providing new information and using recently obtained results to fill in gaps left in the first report. This supplementary report is scheduled to be finalised in February 1992.

We have specifically been asked to provide information on three short-term objectives:

1 Identify present studies on the impacts of climate change and gaps in those studies.
2 Indicate the monitoring required to support the impact studies.
3 Update the First Assessment Report.

This more extensive project was, however, carried out for the Ministry of the Environment and the Directorate for Nature Management in Norway, and has the following objectives:

1 Through studies of recent literature we shall attempt to reveal new information about critical levels/rates of climate parameters, tolerance limits of species and communities, and the probable patterns of ecological change in a new climate regime.
2 The identification of sensitive biomes in Norway and the processes which are likely to have major effects on them.
3 The identification of plant species and communities sensitive to changes in the climate in sensitive biomes.
4 The evaluation of the effects of climate change on the biodiversity of sensitive biomes and on rare or threatened species.
5 To determine whether changes in plant communities will develop linearly or in sudden "jumps".

2 Climate scenarios

A group of Norwegian scientists (Eliassen et al. 1989, Blindheim et al. 1990) has evaluated results from global climate models (GCM) with the aim of preparing various scenarios for future climate changes in Norway. **Table 1** shows the most realistic doubled CO_2 scenarios for Norway. A scenario giving a higher but not unrealistic change is given.

Temperature and precipitation scenarios for Norway (cf. Eliassen et al. 1989) can be summarised:
- the average winter (December, January, February) temperature will increase by 3-4°C, the north-south gradient for this increase being expected to be small; the increase will be smaller in coastal areas than inland
- the average summer (June, July) temperature will increase by about 2°C
- precipitation will increase in all seasons, but will be most pronounced in spring
- a larger proportion of the precipitation will fall as showers.

The balance between precipitation and evapotranspiration gives the hydrological conditions at a specific site. Based on the Norwegian climate scenario, the Norwegian Water Resources and Energy Administration (NVE) has carried out a study on the im-

Table 1 *Doubled CO_2 scenarios for Norway. Numbers in brackets denote high, but not unrealistic changes.*

	Coast	Inland
Temperature changes, degrees		
winter	+3.0 (+3.5)	+3.5 (+5.0)
summer	+1.5 (+2.5)	+2.0 (+3.0)
Precipitation changes, %		
spring	+15 (+15)	+10 (+15)
summer	+10 (+15)	+10 (+15)
autumn	+ 5 (+20)	+ 5 (+20)
winter	+ 5 (+15)	+ 5 (+15)

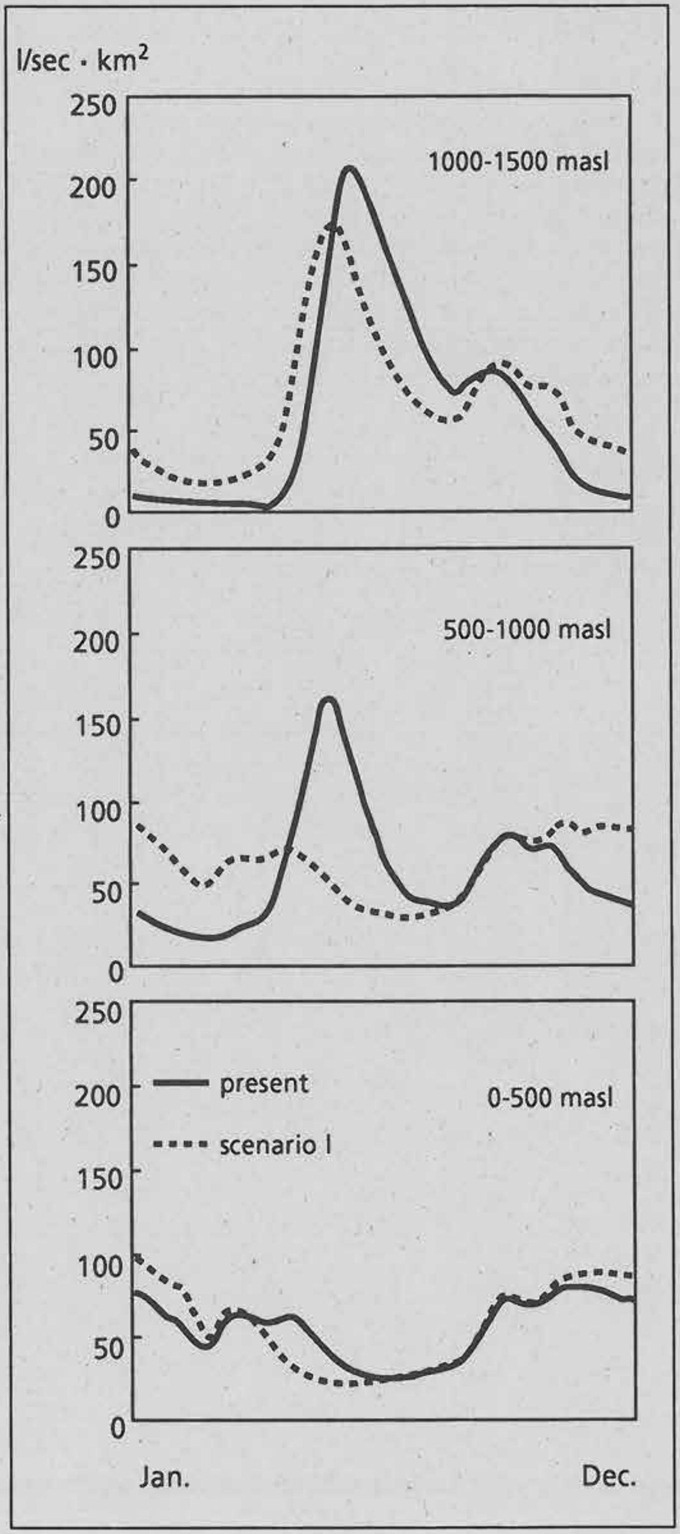
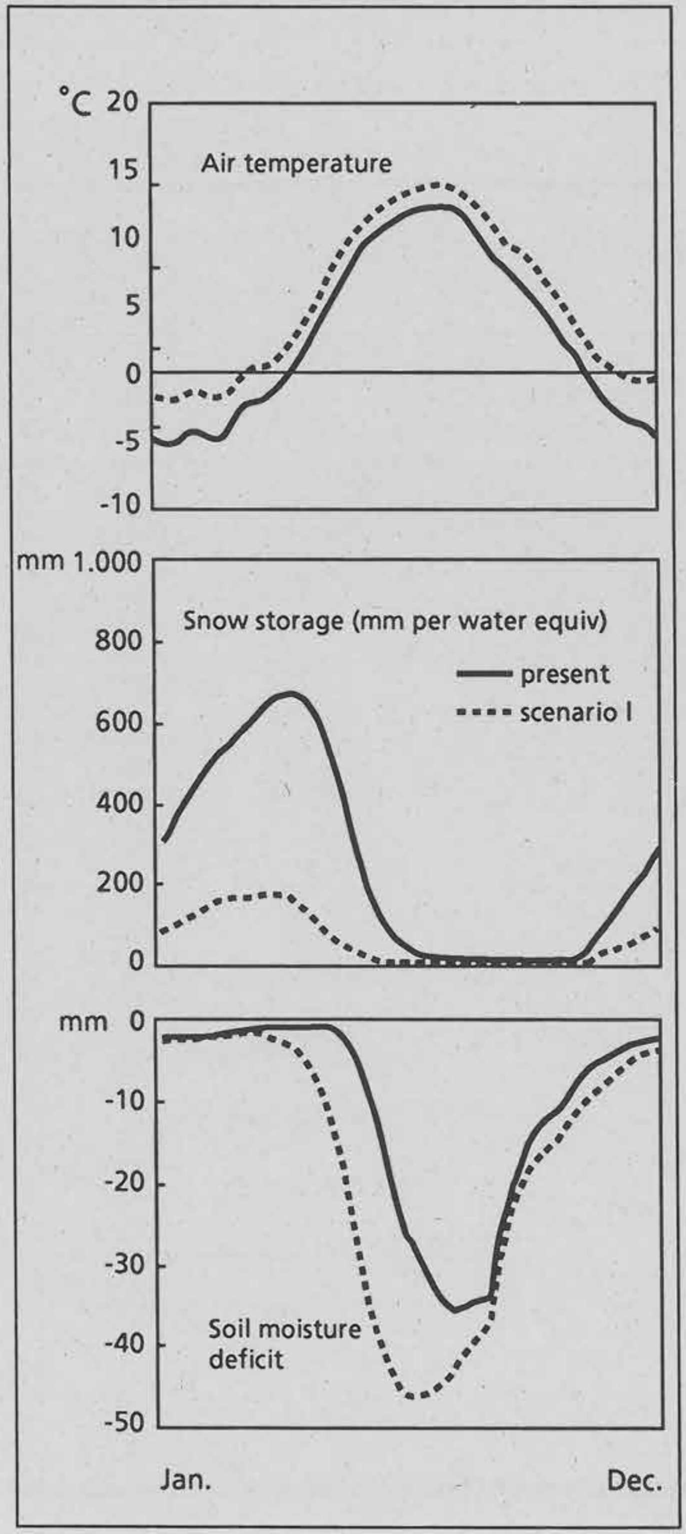


Figure 1
The runoff changes in the three elevation bands, 1: 0-500 m a.s.l., 2: 500-1000 m a.s.l., 3: 1000-1500 m a.s.l. of the River Vosso, western Norway. After Sælthun (1991).



pacts of climate change on the water resources of Norway, including potential changes in hydrological conditions (Sælthun et al. 1990, Sælthun 1991). The main part of this study is a simulation of the **runoff** of seven Norwegian watercourses over a 30-year period, both for the present climate and for the two scenarios (see **Table 1**). The model used also predicts changes in the **snow cover**, **soil moisture** and **ground water** regimes, all of these being very important physical variables for providing more reliable ecological scenarios for Norway.

The hydrological simulations give interesting results, perhaps especially for the River Vosso in western Norway. Substantial hydrological changes are predicted for the elevation zone of 500-1000 m a.s.l., giving a higher winter flow and loss of the spring flood (see **Figure 1**). This resembles the current hydrological regime in England.

Changes in temperature, precipitation and hydrology have important secondary consequences for the duration of snow cover and the **soil moisture deficit**. The duration of **snow cover** on the ground will be reduced by one to three months, the most extreme changes being in central mountain districts (see the simulations for the rivers Lalm and Otta in Sælthun et al. 1990). The most probable scenario suggests, that the **soil moisture deficit** will increase, especially in the growing season and especially in eastern Norway (the counties of Hedmark, Oppland and Buskerud) and the county of Finnmark (see **Figure 2** & **3**).

Other ecologically important consequences following the hydrological simulations (Sælthun et al. 1990, Sælthun 1991) are:

- the **glaciers** will decrease, particularly glaciers in inland areas **erosion** and **sediment transport** are expected to increase greatly during winter
- **flood damage** is expected to increase.

Changes in the local climates towards higher thermic oceanicity may take place, since many of the larger lakes in southeastern Norway are expected to lack an ice cover in most winters.

Figure 2
Changes in a: snow depth b: soil moisture deficit for the River Vosso, western Norway. After Sælthun (1991).

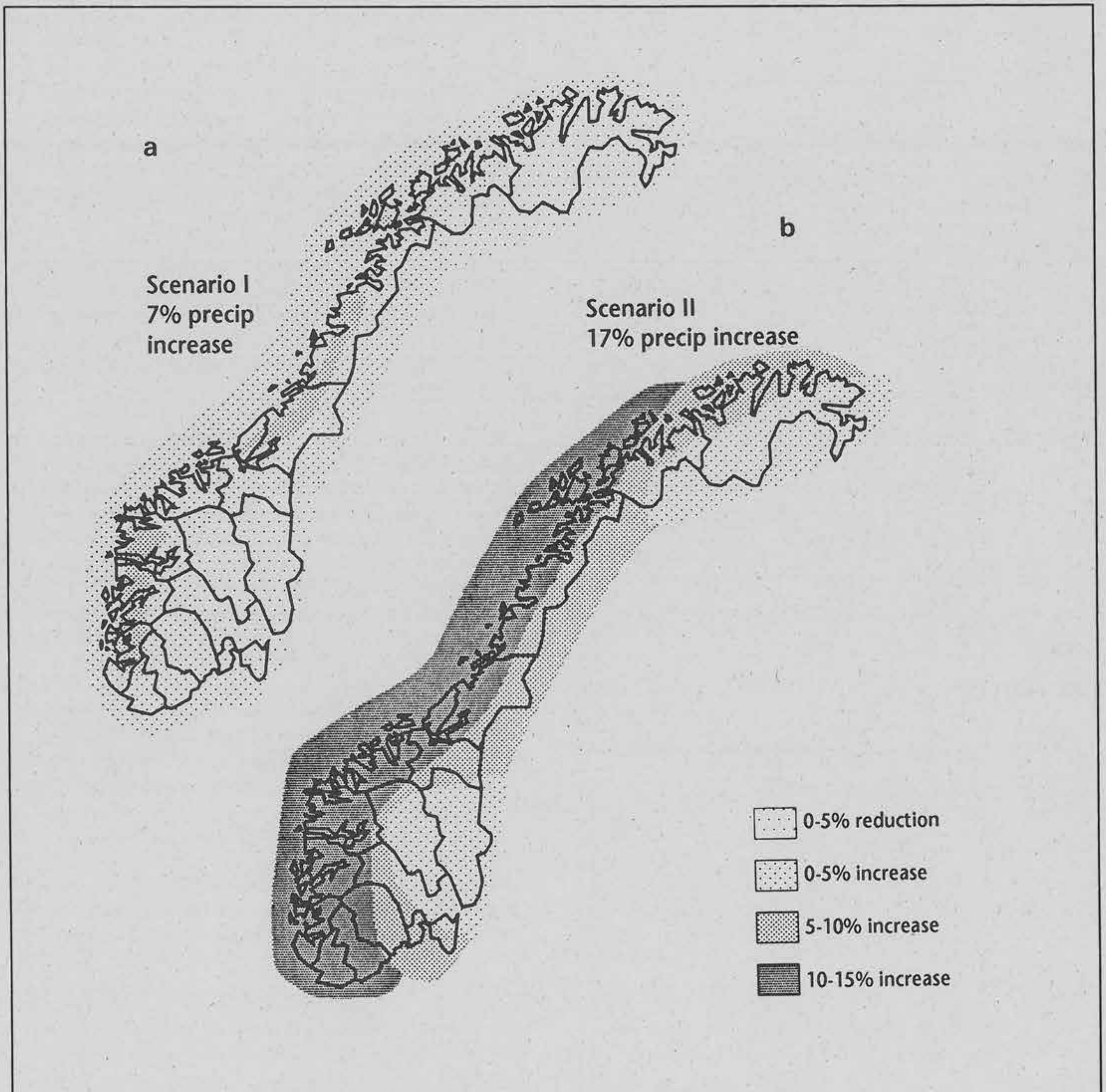


Figure 3

The predicted changes in runoff from two scenarios a: 7 % precipitation increase and b: 17 % precipitation increase based on the hydrological simulations of eight Norwegian river systems. After Sælthun (1991).

3 Background

3.1 State-of-the-art ecological scenarios

All the national contributions to the Intergovernmental Panel on Climate Change (see Izrael 1990) about the ecological impacts of climate change on natural terrestrial ecosystems have revealed severe threats to the natural biota, especially for the boreal and arctic zones. The impact scenarios predict changes in the conditions for production, biogeographical conditions, species diversification and the regional distribution of the biota, all of which will have major ecological consequenses. Some reports give specific lists of species and communities that are under threat or that will be considerably changed (e.g. Hebda 1990, Holten 1990a, b, Cannell 1991, Cannell & Hooper 1991, Leemans 1990, Boer et al. 1990).

Much concern is expressed about the effect of the anticipated high rate of climatic change (Davis 1990). Will species be able to move to their new climatically optimum area before they are left outside their climate space and then become extinct? Will the species be able to establish themselves in their new habitat?

For the temperate zone and the southern part of the boreal zone, the existence of natural and anthropogenic dispersal barriers is treated as a problem of its own. Landscape fragmentation (agriculture, forestry) may become a serious problem for **thermophilous**, southern species whose climate space will be moved northwards (see Turner et al. 1989).

A large number of boreal species, e.g. *Picea abies*, *Aconitum septrionale*, *Carex* spp. and *Salix* spp., (for Norwegian and English plant names, see Appendix), **require chilling** or an annual period with temperatures well below zero ($^{\circ}$C) if they are to survive. Dahl (1990) believes that this type of physiological response is under threat on the western edges of the continents which, according to the climate scenarios, will become much more thermic oceanic.

Many **frost-sensitive** species, i.e. thermic oceanic species, will be favoured by the new conditions and may migrate northeastwards in Europe, for example, *Ilex aquifolium*, *Fagus sylvatica* and *Erica cinerea* are well-known European species that will show this type of physiological response.

Some authors emphasise the potential **weedification** of natural flora (Ketner 1990) and the increase of pioneer species (*Betula* spp.) and annuals.

The alpine and arctic environments will meet many threats, not only because of the changing climate regime, but perhaps more due to competition with the boreal species following the elevation of the alpine and arctic timberlines.

The entire ecological research community emphasises the urgent need for research and monitoring related to changes in climate. Research requirements embrace observations, experiments and modelling, as well as a need for more general ecological knowledge.

3.2 Direct and indirect effects of increased levels of carbon dioxide in the atmosphere

An increase in the CO_2 concentration of the Earth's atmosphere is likely to have both direct and indirect effects on plant communities around the world (Tegart et al. 1990). The direct effects will be due to changes in the physiological responses of plants to elevated levels of CO_2. Increased CO_2 levels will enhance the photosynthesis of many plants (Bazzaz 1990). Different species will apparently respond differently to this increase in CO_2 (Garbutt et al. 1990) e.g. Plants with a C_3 metabolism generally show a greater response to elevated levels of CO_2 than those with a C_4 metabolism (Collins & Jones 1985, Woodward et al. 1991). The indirect effects of elevated CO_2 on plant communities will be due to changes in the climate.

Changes in the climate will not produce an instantaneous shift in the distribution of plant species or communities (Davis 1989, Huntley 1991). Climate change will only have an effect on the vegetation in natural ecosystems if that change causes changes in the population dynamics of the species living there. The size of a population of plants (N) at some point in the future (t+1) is dependent on only five parameters

Equation 1

$$N_{t+1} = N_t + (B-D) + (I-E)$$

where N_t is the number of individuals at time t, B is the number of new individuals (births) appearing between time t and time t+1, D is the number of individuals dying in the same period, I is the number of immigrants into the area and E is the number of emigrants from it. The population size at time t+1 can also be expressed as

Equation 2

$$N_{t+1} = \lambda . f(N_t)$$

where λ is the reproductive rate of a population and $f(N_t)$ is a density-dependent function (Hassell 1975, Watkinson 1980). The reproductive rate of a population is derived from life-table and fecundity schedules (Leverich & Levin 1979) and in the case of perennial plants also requires the use of matrix algebra (Caswell 1989).

In most plant communities, the population of one species can only increase at the expense of another. In order to predict changes in the composition of plant communities and where these communities will occur we have to consider two main points. The first is, what, if anything, is going to reduce the populations of existing species? Changes in climate could detrimentally affect the performance of species directly, e.g. a reduction in snow cover can lead to Norway spruce (*Picea abies*) being damaged by exposure to frost (Kullman & Högberg 1989). The effect could also be indirect, e.g. the competitive pressure of one species on another may increase under new climate conditions (Tallis 1991). The second point to consider is, how are other species going to replace the species lost? The arrival of new species or an increase in the abundance of an existing species will be a result of an increase in the number of births in a population which in turn is a result of the immigration of seeds and their establishment or the vegetative spread of clonal plants. A seedling will only establish if there is a gap in the canopy. Fire, floods, wind, frost, grazing and trampling are just some of the factors which can cause the death of plants and the appearance of gaps. As most seeds land very close to their parent (Watkinson 1978, Okubo & Levin 1989, Carey 1991), the most likely individual to fill a gap is the offspring of a neighbouring plant but there is a smaller chance that a seed from further afield might germinate and establish there. Determining the frequency, intensity and size of gaps and the probability of gap colonisation by particular species are the most important parameters in determining the population size of a species in the future and hence the nature of the community.

4 Sensitivity of biomes to climate change

4.1 Temperate zone (nemoral zone)

Present range. The temperate (nemoral) deciduous forest region currently covers only 0.7% of the total land area of Norway. The coherent temperate zone is confined to the southern tip of Norway (see the map of Dahl et al. 1986), between Arendal in the east and somewhat west of the Lista peninsula.

The climate space of the temperate zone in Norway lies in the mean temperature interval of 0°-+1°C for January and 15°-17°C for July. The growing season is therefore fairly long, about 6-7 months. The annual precipitation is about 1000 mm.

Main plant communities. Two oak forest communities characterise the temperate zone:
- oak forest with Vaccinium myrtillus
- oak forest with low herbs.

Zone shift predicted by climate variables. With the warmer winters and summers predicted by the scenario used in this report (Eliassen et al. 1989) large areas of the south of Norway will match the climate conditions of the present temperate zone by 2030. This new temperate zone will be almost identical in extent to the present hemiboreal zone (**Figure 4**) which includes Oslo. In western Norway, south-facing slopes along the inland shores of fjords, which are currently within the hemiboreal zone, will fall in the temperate zone by 2030. The new temperate zone (**Figure 5**) will in fact extend as far north as Mo i Rana, northern Norway.

Predictions based on climate, hydrology and population dynamics. The climate of the current temperate zone in Norway is likely to become much more like the south of England. The vegetation of this part of Norway, however, is not likely to change so that it matches the vegetation of that area. The closed canopy of temperate forests makes them difficult for new species to invade. Species such as beech (*Fagus sylvatica*), which should be favoured in this future climate, especially on shallow soils, will suffer competitive pressure from existing tree species. Beech is, therefore, unlikely to produce the extensive stands seen in ancient woodlands of eastern Europe and southern England. Beech and other temperate species from the south and west are likely to appear as individuals in existing stands, having spread naturally from continental Europe. They are most likely to

Figure 4
The vegetational zones of Norway from the map issued by Nordiska Ministerrådet (1984). 1 (black): alpine zone, 2: northern boreal zone, 3: mixed southern, middle and northern boreal subzones, 4: middle boreal subzone, 5: oceanic middle boreal subzone, 6: southern boreal subzone, 7 and 8: hemiboreal zone, 9: temperate zone.

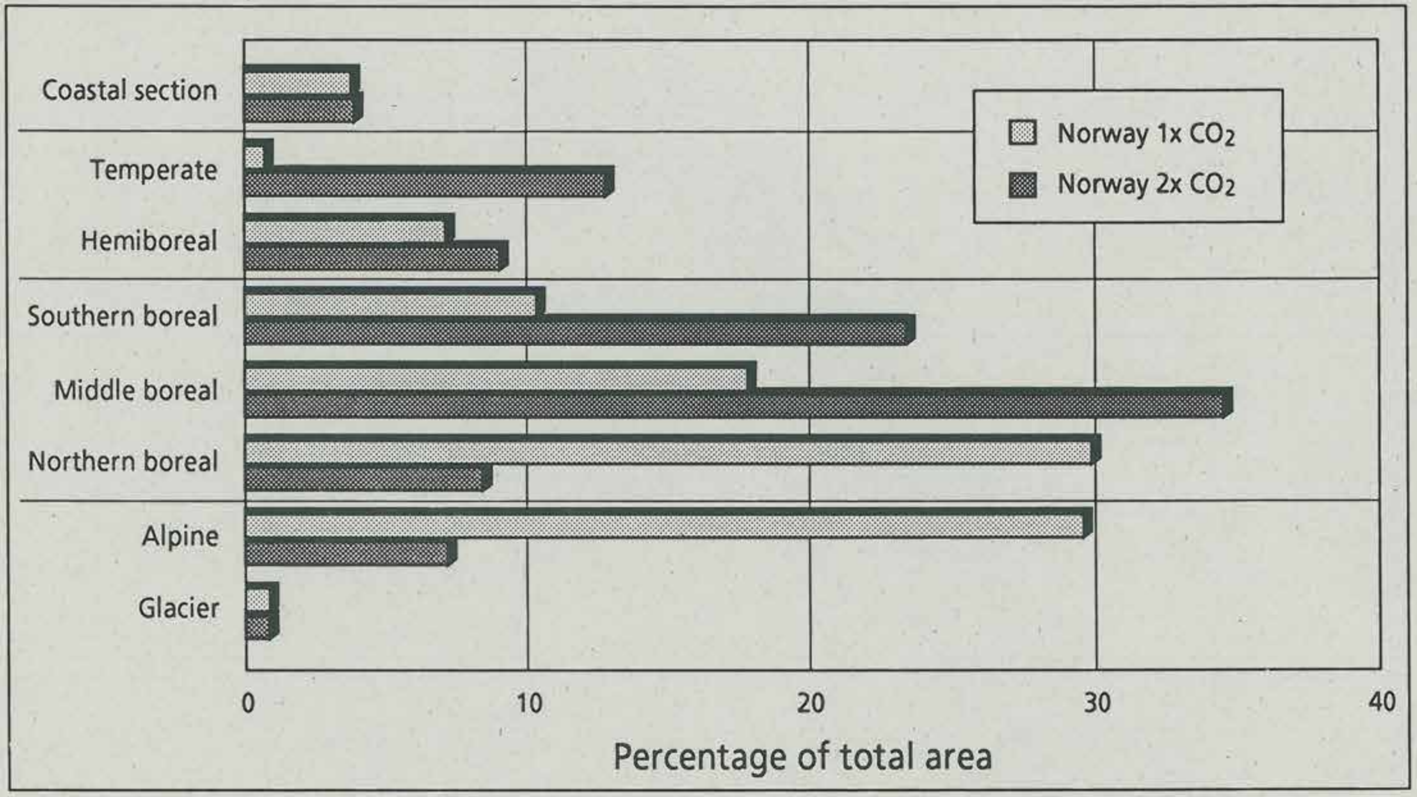


Figure 5

The current and predicted areas of the Norwegian vegetation zones; the coastal section and the glaciers are unchanged.

occur, however, as a result of planting or dissemination from planted trees already existing in Scandinavia. The extremely low probability of a seed germinating and establishing in an existing forest will be increased by the appearance of more gaps. Gaps are most likely to be caused by storm damage or clearance by man. Although fires may be another cause of these gaps, especially if summer droughts become more common.

The spread of temperate forests northwards will in part be determined by where man allows them to go. Patches of naturally occurring temperate woodland are rare and they are often isolated from one another. In the present hemiboreal zone, the area of Norway that is predicted to be suitable for temperate forest invasion, patches of natural woodland are even less common and are more isolated than in the temperate region. Temperate species can therefore not move northwards in a continuous slowly moving wave, but must depend on "island hopping" tactics if they are to spread.

Forest margins and marginal communities may prove to act as some sort of "corridor" for species to move along (reviewed by Hansson 1991). For plants, which have only a small probability of landing in a forest margin, these are likely to prove less effective than for animals that can consciously use them.

A factor that further reduces the rate at which these species can fill their new climate space is the presence of substantial natural barriers (**Figure 6**), notably the mountains and fjords. There is only a small probability that temperate plant species will be carried naturally to the areas around Mo i Rana, for example. All the temperate species will certainly not arrive simultaneously in the new climate space. Some species may be able to spread by 2030, but unless they are specifically planted it will be difficult to tell which these will be. The tree species that are more likely to increase in abundance are those found in both the temperate and hemiboreal regions, e.g. oak (*Quercus* spp.).

All species considered so far have been dominant forest tree species. It is difficult to assess how quickly the ground flora will be

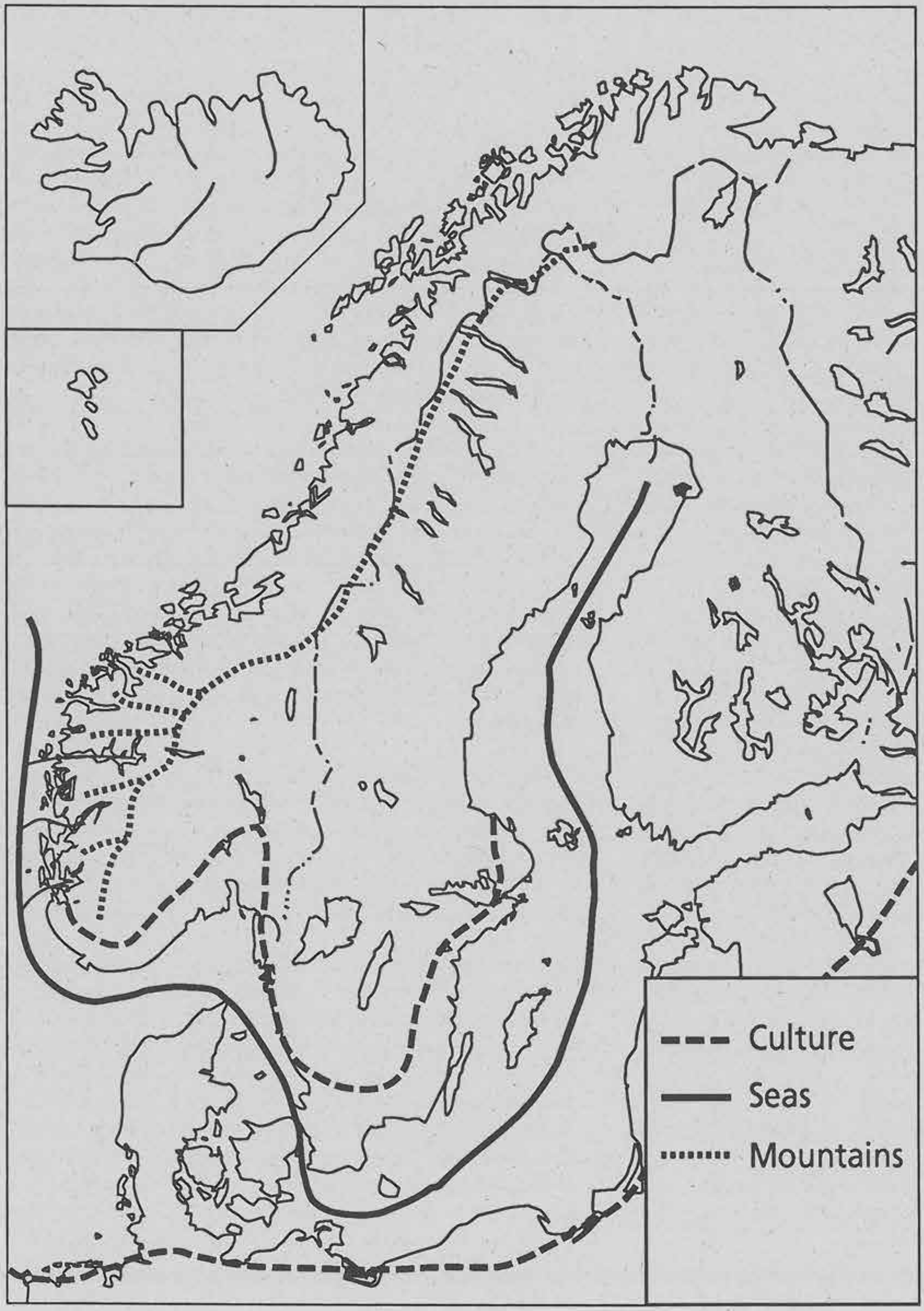


Figure 6
The possible position of the barriers to the migration of thermophilous species in northern Europe. These barriers are both natural, 1: seas (——), 2: mountains (▪▪▪▪▪▪) and anthropogenic, 3: agriculture, forestry and communications (▬ ▬ ▬).

able to spread northwards. Some general points will be of relevance, however. Plant species bearing edible fruits (e.g. *Vaccinium myrtillus*) are quite likely to be carried to new habitats by animals (especially humans). Wind-dispersed woodland species (e.g. *Holcus mollis*) may take longer. Species which normally only reproduce vegetatively and are restricted to woodland (e.g. *Mercurialis perennis*) are not likely to increase their distribution very much, if at all.

Weedy, annual species of open ground (e.g. *Bromus mollis* and *Geranium molle*) are likely to be some of the first indicators of a shift in climate space. This is mainly because of the availability of open ground, either due to natural phenomena such as fires or landslides or man-made "waste ground",for example, at the sides of roads and railways.

Another annual grass species, *Bromus sterilis*, may become more widespread and more abundant, at least in south and west Norway. In the UK, this species is an arable weed which has a large effect on crop yields and is of economic importance.

4.2 Hemiboreal zone (boreonemoral zone)

Present range. This mixed forest zone is transitional between the southern temperate zone and the northern boreal zone. The zone covers a fairly broad, coherent belt in the lowlands up to 300 m a.s.l. in southeastern Norway (Dahl et al. 1986). Due to topography, the hemiboreal zone is very discontinous in western Norway. In all, it covers about 7.1% of the land area. It occupies a much broader climate space than the temperate zone and therefore has a fairly high floristic diversity. The hemiboreal zone in Norway is defined by mean temperature intervals of -7°-+2°C for January and 14°-18°C for July. The hygric conditions are also very variable in this zone, the annual precipitation ranging from about 600 mm in the Mjøsa district in inner southeastern Norway to more than 2000 mm in middle fjord districts in western Norway.

Main plant communities. Three plant communities dominate the hemiboreal zone (HB):

- Ulmus glabra-Tilia cordata forest (warm and dry slopes).
- Alnus incana-Fraxinus excelsior forest (along water courses in southern and southeast Norway).
- coniferous, birch and grey alder forests (on oligotrophic and less warm sites in the HB zone).

Zone shift predicted by climate variables. The present hemiboreal zone (**Figure 4**) will also be shifted northwards by 2030. The predicted climate changes (Eliassen et al. 1989) suggest that sheltered, south-facing, inland fjord slopes as far north as Narvik will be able to support typical hemiboreal vegetation. Much of this new hemiboreal zone will fill the space occupied by the present southern boreal zone (**Figure 4**) including most of southern Hedmark and southern Oppland. In many fjords of southwestern Norway, the hemiboreal zone will reach from the shore on the north-facing, inland slopes to an altitude of approximately 300-400 m. On the south-facing slopes in the same fjords the new hemiboreal zone will be above the new temperate zone from an altitude of 300 m to one of 700-800 m. Much of the low-lying land in Nord-Trøndelag and Sør-Trøndelag, for example, will be in this new hemiboreal zone.

Predictions based on climate, hydrology and population dynamics. The spread of woodland species of the hemiboreal zone northwards will be controlled by many of the same population factors that will control the spread of the temperate species. As the rate of spread of a population is related to the number of individuals in the population, the rarity of natural hemiboreal forests is an additional factor of great importance. The closed spruce and pine forests of the boreal region are very shaded and only species which can survive in a dark understorey will spread into the forest unless a large gap is caused by fire or a landslide, for example.

The dominant forest communities (with *Picea abies*, *Betula pubescens* and *Alnus incana*) of the hemiboreal zone are highly managed and are unlikely to be greatly affected by changes in climate. There may be changes in the herb layer after stands of *P. abies* are clear felled, with more thermophilous southern species becoming more abundant.

The frequent natural hemiboreal community, the thermophilous *Ulmus glabra-Tilia cordata* forest, may change dramatically if a warmer climate allows the spread of the beetle which carries "Dutch elm disease". This disease will cause the death of most the elm (*U. glabra*) trees in Scandinavia. Note, however, that in the U.K. *U. glabra* showed more resistence to this disease than *U. procera*. *U. glabra* will probably be replaced by other tree species already found in the hemiboreal forests. Hazel (*Corylus avellana*) could become much more abundant, for example. This is a species that is believed to be suppressed due to competition from other tree species. It is thought that in the early Holocene this was one of the species that migrated very slowly in response to climate change when faced with other tree species (Deacon

1974). Investigations of pollen records show that another hemiboreal species, ash (*Fraxinus excelsior*) had the slowest migration rate (2.5 km/century) of any tree taxa during the early Holocene period (Huntley & Birks 1983). This may indicate that ash will respond slowly again, although the "sudden" disappearance of the *U. glabra* may allow an unusually large number of gaps for the establishment of seedlings of this species.

4.3 Boreal zone

Present range. The boreal zone is the main forest zone in Norway and Scandinavia. It is a coniferous-forest dominated zone with an east-west extension of about 8000 km throughout Eurasia. In Norway, the boreal forests vary a great deal and are characterised by the proximity of the Atlantic Ocean, both in thermic and hygric respects, and therefore its floristic respect as well. Along the east-west gradient in Scandinavia, the southwest- northeast-trending Scandes mountain range defines a sharp climatic and ecological boundary, giving the forest communities on the western side of the range a much more oceanic character than those on the eastern side which have a continental character.

The south-north extension of the boreal zone is also very broad. It has therefore been found expedient to divide the zone into three, the southern boreal, middle boreal and northern boreal subzones. The northern boreal subzone is limited upwards by the alpine timberline which is located at a maximum of 1200 m a.s.l. in southern Norway and 800 m a.s.l. in the central northern part of the Scandes chain. Since ecologists do not recognise a real arctic zone in Scandinavia, the boreal zone extends to the Arctic Ocean.

The climate space of the Norwegian boreal zone is very wide. If we include the coastal section (Dahl et al. 1986), the approximate climate space will be defined by the temperature interval of +1°C to -15°C for January and 10°C to 14°C for July. The hygric conditions also vary greatly, from the dry inner valley bottoms of southern Norway that have less than 300 mm annual precipitation to the very wet upland districts of middle fjord districts in western Norway that have more than 3000 mm annual precipitation. Hence, in both thermic and hygric respects, the Norwegian boreal zone is very diverse.

The following three climatic factors seem important for the ranges of boreal plant communities and species:
- **summer temperature** defines the upper and northern limits of most species (energy demand limit)
- **winter temperature** controls the western limits of typical boreal species that avoid mild winter climates
- **hygric oceanicity** (annual precipitation, frequency of rainfall) very often defines both the upper and western limits of continental boreal species (e.g. Festuca ovina).

Main plant communities. Southern boreal subzone (SB) is characterised by the predominance of
- low herb forests
- Alnus incana-Ulmus glabra forest
- Alnus incana-Prunus padus forest

Middle boreal subzone (MB). The most wide-ranging community in MB is
- Picea abies/Betula pubescens forest with Vaccinium myrtillus

Mesotrophic and damper sites have
- tall fern forests

A continental forest community that has its optimum in MB is
- lichen - pine forest

Northern boreal subzone (NB). Probably the most dominant community is
- birch forest with Vaccinium myrtillus

A very open woodland community in the most oligotrophic, continental, winter-cold areas is
- lichen-birch forest

whereas lower elevations here are characterised by
- lichen-pine forest

Calcareous, damp, steep slopes may be dominated by
- tall herb-birch forest.

Zone shift predicted by climate variables. The predicted climate space for the boreal zone in Norway will also include much of the present mountain plateaux of Hardangervidda in southern Norway and Finnmarksvidda in northern Norway. This will lead to a great increase in the middle boreal subzone, whereas the northern boreal subzone will shrink to survive as islands, especially in eastern central Norway and Finnmark (see **Figure 5** and the map of "Potential vegetation regions for Norway" in Holten (1990b)). The upper limit of the boreal zone is defined by the alpine timberline. The predicted upward shift of this timberline is 200-300 m vertical displacement for coastal and fjord districts and 300-400 m for inland parts in southern Norway. The maximum height of the new climatic timberline in southern Norway will therefore be 1500-1600 m a.s.l., highest in the Jotunheimen-Dovrefjell region.

On the whole, Scots pine (*Pinus sylvestris*) may also be favoured in the southern and middle boreal subzones in southeastern Norway at the expense of Norway spruce (*Picea abies*). This reasoning is based on the hydrological simulation of the River Otta (see Table A.2 in Sælthun 1990), which indicates that 25 days of the growing season will have a soil-moisture deficit of more than 50 mm between 0 and 1000 m a.s.l. The same scenario indicates a reduction in the duration of snow cover of 1.5 to 2.5 months. An increased soil-moisture deficit and a longer growing season may lead to more steppe-like conditions locally in the dry, inner valleys of southeast Norway, at least on steep, south-facing slopes. Combined with moderate grazing, this may favour *Fectuca ovina* communities with or without Scots pine.

Predictions based on climate, hydrology and population dynamics. The main coniferous forests of the boreal zone will probably not alter drastically for many decades or centuries because they are highly managed and consist of dense stands of trees which are difficult for shade-intolerant species to invade. Some invading thermophilous tree species will manage to establish in gaps. Unless the gaps are large (100 hectares) and occur frequently the invading trees will not alter the main character of the forest.

Some communities in the boreal zone may, however, change considerably more quickly than the conifer forests as the climate changes. The already herb-rich *Alnus incana-Ulmus glabra* community of steep south-facing slopes may become even more herb-rich if Dutch elm disease kills the *U. glabra* leaving a large number of gaps in the canopy. This increase in herbaceous vegetation will only be temporary. A new cohort of trees will replace the *U. glabra* although it is not clear which species these will be.

The *A. incana-Prunus padus* community of river valleys may be affected by the change in hydrology of the regions in which it is found. In valleys in South-East and Central Norway the reduction in spring floods may dry the soil and allow *Picea abies* to invade from the slopes above the *A. incana-P. padus* woods. This community is also found on steep slopes on heavy clay soils, and these, too, may be affected by changes in precipitation and hydrology. An increase in freeze/thaw processes in the winter and heavier storms in summer may lead to an increase in landslides on these heavy soils below the upper marine limit. The resulting gaps may well be re-invaded by the same species, but the age structure of the population will be greatly altered. If landslides or other disturbances occur regularly, the age structure of the forest will become much more diverse. There will be areas of mature trees, dense areas of juvenile trees or scrub, and a rich herb layer will be more prominent in the early stages of succession.

Ombrotrophic bog communities could be affected by the changing climate, especially if there are longer periods of drought in the summer. This scenario is predicted for eastern Norway and Sweden. If the bogs become drier, species currently occupying the drier hummocks (*Calluna vulgaris* and lichens) will move down into what are now the wetter lawns dominated by (*Scirpus cespitosus*). *Picea abies*, *Pinus sylvestris*, *Alnus incana*, *Betula pubescens* and *Salix* spp. will encroach at the edges of the bog unless there are regular disturbances, such as fire. Grazing by moose may also limit the deciduous species. Herbaceous species like *Vaccinium myrtillus* may encroach with the trees. The bogs will therefore become smaller unless trees are prevented from establishing. If trees do not invade the bogs, they are likely to become more like heathland. In areas where drought is not predicted to increase in frequency, i.e. western Norway, the bog communities will probably not be altered to any great extent.

The lichen-birch forest of the continental part of the northern boreal subzone is a community which could change very rapidly if the conditions at its southern/lower limits become better suited to *Pinus sylvestris* and *Picea abies* than they are at present. The open nature of the woodland makes it very susceptible to invasion because gaps are already present. The invading tree species will probably not be excluded by competitive pressure from the lichens, at least, not for long. Grazing of the young trees may slow the rate of spread of the coniferous forest northwards/upwards into the lichen-birch forests.

The tall herb-birch forests of calcareous areas in the northern boreal subzone may become less diverse if gaps are caused which allow tree species with a denser canopy than *B. pubescens* to invade from the lower slopes of mountains. This process may take centuries, however.

If Sælthun's (1990, 1991) hydrological scenarios come true, perhaps the greatest changes will take place in the mountain forests (the northern boreal subzone) and the alpine region. These zones, and especially the birch forests, are well adapted to a snowy climate, i.e. to great snow depth and a long duration of snow cover. If the snow cover changes, as indicated in **Figure 2**, this may lay open a major part of the current birch forest in oligotrophic habitats for invasion by Scots pine (*Pinus sylvestris*), since the danger of the pine needles being attacked by the fungus *Phacidium infestans* will be greatly reduced. A reduction in sideways snow pressure on slopes will also favour pine. Spruce (*Picea abies*) may be more competitive on more mesotrophic to eutrophic, north-facing, northern boreal slopes in continental southern Norway. Birch (*Betula pubescens*) may therefore become an even more oceanic (in the hygric sense) tree species, invading new areas in central and western parts of the mountain range, especially under the most extreme precipitation scenario (**Figure 3**).

4.4 Alpine zone

Present range. According to the map published by Dahl et al. (1986), the alpine zone currently covers 29.6% of the land area in Norway. In southern Norway, this zone forms a coherent area from the mountain plateau of Hardangervidda in the south to the Dovrefjell-Trollheimen area in central Norway. Further north, from Børgefjell National Park to Finnmark, the alpine zone is formed by a 200 km broad mountain range on the border between Norway and Sweden.

Broadly speaking, the climate space of the alpine zone is defined by all areas with a July temperature of less than about 10°C. The mean January temperatures there will vary from about -4° to -16°C.

The alpine zone is characterised by a very undulating and variable topography, on both small and large scales. Due to a very windy weather regime, the snow distribution in winter will be controlled by topography, giving snow beds with deep, long-lasting snow and ridges with no snow at any time of the year.

The **snow cover** is regarded as the most important ecological factor in the alpine ecosystems. The snow-cover factor has resulted in many types of physiological response in the alpine zone, from the ridge species that are directly adapted to the weather (strong desiccating winds, low temperatures), via the lee-slope species occupying areas with moderate snow cover in winter, to the snow-bed species that are covered and in many ways protected by the snow for the greater part of the year. It is likely that these three physiologically-differentiated groups of species will respond to a change in climate in different ways (see below).

Main plant communities. Low alpine subzone (LA). Best defined on hard, acidic bedrock by the upper limit of
- Vaccinium myrtillus heaths

and on the less common calcareous substrate by extensive
- thickets of Salix species.

Characteristic for acidic substrate on lee slopes along the snow bed-ridge gradient is a zone of
- Vaccinium myrtillus-Phyllodoce heath.

This lee-slope vegetation is followed downwards by
- grassy snow-bed

The typical, extreme snow-bed community is the
- Salix herbacea snow-bed

Middle alpine subzone (MA)
Perhaps the most typical community is the
- middle alpine grassy heath

High alpine subzone (HA)
The most typical community here is
- Luzula confusa vegetation

Zone shift predicted by climate variables. The climate space of the alpine zone in Norway includes areas having July mean temperatures of less than 10°C. Land areas satisfying this demand will shrink very substantially under the Norwegian climate scenario, at least in the central and eastern parts of the Fennoscandian mountain range.

Predictions based on climate, hydrology and population dynamics. As in the northern boreal region, the dominating climate-induced factor in the alpine zone is snow cover. Snow cover is important for the hydrology, the duration of the growing season and the protection of plants against frost on alpine habitats. The hydrological scenario for the central Norwegian mountains (see Table A.2 in Sælthun 1990) indicates an average reduction of the snow cover above 1000 m a.s.l. of 1.5 months. For other mountainous areas in southern and central Norway, the duration of snow cover will be still further reduced, by 2-3 months, according to Sælthun's simulations. These predicted snow conditions are typical for the present upper middle boreal and northern boreal subzones.

Plant populations in alpine areas are likely to react very slowly to the changes in climate predicted in the coming decades. This can be explained by the short growing season at high altitudes. There is a tendency for species in alpine communities to grow slowly in comparison with species at lower altitudes. As the climate warms, there will be a longer growing season at high altitudes. Even with a much longer growing season, species from the lower slopes will find it difficult to survive in the harsh conditions on mountain tops. Plant communities on high, exposed ridges, typically the *Luzula confusa* community, are therefore unlikely to change markedly in the future, although some more thermophilous plant species will probably become established in sheltered micro-habitats.

On the gradient between the exposed ridges and the base of sheltered slopes away from the wind, where snow may gather, there may be a noticeable difference in the vegetation in the future. It is predicted that the amount of snow falling each winter will decrease. This may have different effects on different species. Some species, for example, depend on snow cover until late in the season to protect their sensitive buds from frost (e.g. *Betula nana*), whilst others (e.g. *Carex bigelowii*) depend on little snowfall to prevent competition from species like *B. nana* and *Salix herbacea*.

In hollows at the very base of sheltered slopes where the snow melts for only one month of the year, non-vascular species (e.g. *Anthelia juratzkana* and *Polytrichum sexangulare*) predominate in the snow-bed community because they only require a very short growing season. As the growing season becomes longer due to the earlier disappearance of the spring snow and the later arrival of the autumn snow, these species will be outcompeted by vascular plant species from around the edges of this most extreme snow-bed (e.g. *Salix herbacea* and *Cassiope hypnoides*). The length of the growing season will also increase in the current *S. herbacea* snow bed, and this will in turn be invaded by species from its edges (e.g. *Nardus stricta* and *Alchemilla alpina*).

The new stress situation on vegetation in the alpine zone will probably favour low-growing dwarf shrub species on the ridges, e.g. Empetrum hermaphroditum, *Arctostaphylos uva-ursi*, *A. alpinus* and *Loiseleuria procumbens*. The effect on *Vaccinium myrtillus*, *Deschampsia flexuosa* and other slope species is more uncertain because the longer growing season will favour them in new areas further down in the snow bed. However, the same species may be exposed to late frosts on their upper limit along the snow bed-ridge gradient.

For many species there will be a trade-off between the benefits of a longer growing season and the damage caused by late frost and desiccation, e.g. for *Vaccinium myrtillus*. The outcome of this trade-off is likely to be different for each species, and without experimentation it is not possible to discuss what this outcome will be.

The lower alpine community is likely to be slowly invaded by boreal tree species as the climate becomes more suitable to them. The harsh environmental conditions at the top of mountains (strong winds, little or no soil) may prevent the upward movement of this lower alpine community. The lower, and perhaps middle, alpine communities will therefore be squeezed into a narrower strip on many mountains. Most of the species within the lower and middle alpine communities are found either in the boreal or in the high alpine community, but at different levels of abundance. Most individual species within the lower and middle alpine communities are therefore not in imminent danger of extinction.

4.5 The arctic zone

Present range. According to Brattbakk's (1986) classification of Svalbard and Jan Mayen into vegetation regions, the terrestrial arctic of Svalbard belongs to the Mid Arctic and High Arctic zone. The Mid Arctic covers most of Jan Mayen and the whole Bjørnøya. On Spitsbergen the warmest parts of the Mid Arctic zone is confined to the central and inner fjord districts, below 300 m a.s.l. It is named the *Cassiope tetragona* zone, and is well correlated with the 6 °C July isotherm. The less thermophilous zone at Svalbard, named the *Dryas octopetala* zone in Brattbakk's map, is more coastal.

The High Arctic zone is mainly represented as orozones at Spitsbergen. At Edgeøya, Barentsøya and Nordaustlandet, all islands being located east of Spitsbergen, the warmest subzone of the High Arctic, the *Salix polaris* zone, is also found at sea level. The warmest parts of the *Salix polaris* zone is correlated with approximately the 2 °C isotherm for July. The least favourable subzone of the High Arctic zone, the *Papaver dahlianum* zone, is mainly found at Edgeøya, Barentsøya and Nordaustlandet in addition to permanent ice cover (see also Elvebakk 1989).

The oceanicity/continentality gradient in the flora and vegetation of Svalbard is pronounced along a southwest/northeast gradient, the most oceanic, both in the thermic and hygric respect, being the southwest coast of Spitsbergen. The fjord site Longeyarbyen is pretty continental, having only 203 mm as annual precipitation (Steffensen 1982).

Main plant communities. (Brattbakk 1979, 1986). **Mid Arctic subzone**.

- Cassiope tetragona heath (Tetragono-Dryadetum) characterizes the most thermophilous plant community at Svalbard

It is differential towards the less thermophilous Dryas octopetala subzone of the Mid Arctic.

- Dryas heath (Dryadion) is zonal vegetation on fairly calcareous ground
- Saxifraga oppositifolia-Cetraria delisei-community. Dominating community in the Dryas octopetala subzone. The most frequent plant community at Svalbard.

High Arctic subzone

- The Saxifraga cespitosa-Poa alpina community forms zonal ve-

getation in the Salix polaris zone. Differential plant community towards the less thermophilous Papaver dahlianum zone
- Salix polaris communities
- "Wet" tundra, including Phippsia algida communities
- "Dry" tundra, including Papaver dahlianum communities

Zone shift predicted by climate variables. The climatically most favourable area for plant growth on Svalbard today is the mid-arctic zone in the fjord districts around Longyearbyen on Spitsbergen (Brattbakk 1986). The mildest parts here have July isotherms of about 6 °C. The predicted increase of 2-3 °C for the summer temperature should lead to thermically northern boreal growing conditions on some south-facing patches in this area at 78 ^{O}N.

Predictions based on climate, hydrology and population dynamics. In Svalbard, the extreme climatic conditions, with a short growing period, mean changes in vegetation will probably be very slow. Most of the vegetation is long lived and slow growing. It has been feared that rapid warming in the mean annual temperature of arctic regions will cause the extinction of many species. Past events, notably the warming during the early Holocene, indicate that most species will decline in abundance but will survive within refugia. In Great Britain, for example, only 12 of the 444 species recorded from the last glaciation have become extinct since. Many of the alpine species only exist now on a few hillsides in Scotland where their persistence can be attributed to micro-climate and a low level of competition from more temperate plants. It is also worth noting that forests do not exist on these mountains due to clearing and subsequent grazing.

Some species will almost certainly be threatened with extinction. Annuals are probably most at threat as one catastrophic year could cause the extinction of whole populations, especially if the species has a very small, or no, seed bank.

The plant communities of Svalbard may be protected from invasion by boreal species because they are islands. The large expanse of sea between the mainland and the islands will present a major barrier to dispersal. However, many more thermophilous species have been brought to the islands, most of them accidentally, by man. These species survive around the settlements where conditions are most favourable. These populations could present foci for invasions if the climate becomes warmer. Most of these species are annuals and are unable to produce viable seed at present because of the short growing period (Rønning 1971). In 1971, Rønning listed seven species (*Capsella bursa-pastoris*, *Deschampsia cespitosa*, *Poa pratensis*, *Matricaria inodora*, *Ranunculus acris*, *Rumex acetosa* and *Rumex acetosella*) which could be considered as true introductions to the flora. Of these the perennial grasses could have the greatest effect, by filling in gaps in the sparse vegetation of the drier communities and later replacing much of the existing herbaceous plants by competitive exclusion. *Ranunculus acris* could become an abundant plant in damp areas amongst grass and sedge species. The annual species, e.g. *Rumex* spp., could invade open, dry areas quickly, but are unlikely to outcompete the local perennial flora.

The small patches of *Betula nana* on Svalbard may become larger with the 2 x CO_2 scenario. The populations might be genetically depauperate, however, and this may prevent a large viable population being formed. The genetic variation of the population should be increased sufficiently with the addition of pollen or seeds that will be brought from the mainland.

5 Correlative model for distribution of types of physiological response

5.1 Introduction

Correlative models have the great advantage that they need no ecophysiological explanation for the distribution pattern of a certain plant species or plant community. Instead, some of the correlative models are based on hypotheses about which factors control or limit the distribution of plants. If gridded data are available for the distribution and essential climatic parameters, correlative models of this sort may be very useful for predicting the future distributions of certain plant species or groups of species that are suggested to represent types of physiological response (see Dahl 1951, Dahl 1990, Skre 1979).

5.2 Predictions

Predictions have been made on patterns of vertical plant distribution in central Norway using a simple correlative model with presence/absence distributional data in grid cells (horizontal axis 5 km, vertical axis 100 m) and associated climatic parameters. The climatic parameters were July mean temperatures, January mean temperatures and annual precipitation (Holten 1986, 1990a). This correlative model is based on the following three hypotheses.

- **Thermic oceanicity** (winter temperatures) defines the eastern limits of frost-sensitive coastal plants (e.g. Ilex aquifolium, Erica cinerea, Hypericum pulchrum) and the western limits of eastern plants that avoid areas with mild winters (e.g. Picea abies, Aconitum septentrionale, Viola mirabilis).

- **Summer temperature** defines the upper limits (high temperature demands) of certain thermophilous, lowland plants (e.g. Ulmus glabra, Corylus avellana, Bromus benekenii) and the lower limit of some mountain plants (Salix herbacea, Phyllodoce caerulea, Saxifraga aizoides).

- **Hygric oceanicity** (humidity) defines the eastern limits and sometimes the lower limits of humidiphilous coastal plants, e.g. Blechnum spicant, Thelypteris limbosperma, Narthecium ossifragum) and the western and/or upper limits of continental, xerophilous plants (Carex ericetorum, Androsace septentrionalis, Festuca ovina s. str.).

The predicted response in the above-mentioned ecological types, using a 2°C increase for July temperatures and a 4°C increase for January temperatures, is indicated in **Figures 7** and **8** on the species level and **Figures 9** and **10** on the community level (compare Holten 1990a). Holten's (1990a) correlative model predicts the following responses for the above-mentioned types of ecology and distribution in Norway:

- frost-sensitive species will expand eastwards in western Norway
- some boreal species will retreat or be threatened on their western limit
- humidiphilous coastal plants will probably retreat
- xerophilous continental plants will expand
- thermophilous species will expand upwards and northwards
- alpine plants will retreat and some will even be threatened.

Dahl (1990) has used essentially the same correlative model for Norway spruce (*Picea abies*) and beech (*Fagus sylvatica*), distribution data for which were digitised from Atlas Flora Europaea (Tutin et al. 1965-90), with an associated climate data base for the same grid cells (50 x 50 km). His model predicts a potential expansion of beech in eastern Europe (**Figure 11 A** & **B**) and a retreat of Norway spruce in central and southeastern Europe (**Figure 12 A** & **B**).

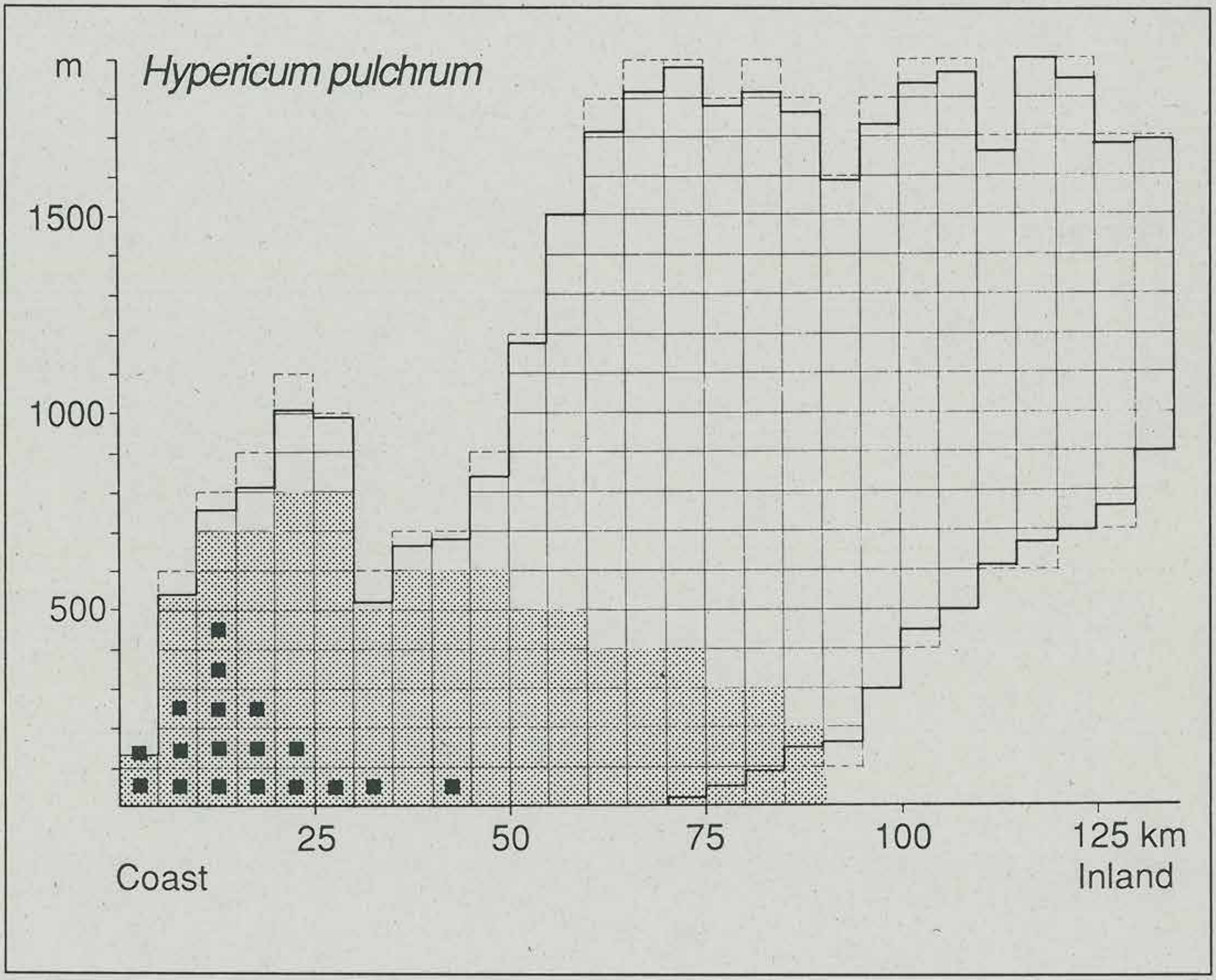


Figure 7a
Correlative models showing the current (■) and predicted (░) vertical ranges of a: the coastal, frost-sensitive species Hypericum pulchrum *and b: the continental species* Viola mirabilis. *Both models are based on the Norwegian climate scenario, including a 2°C increase in summer temperature and a 4°C increase in winter temperature.*

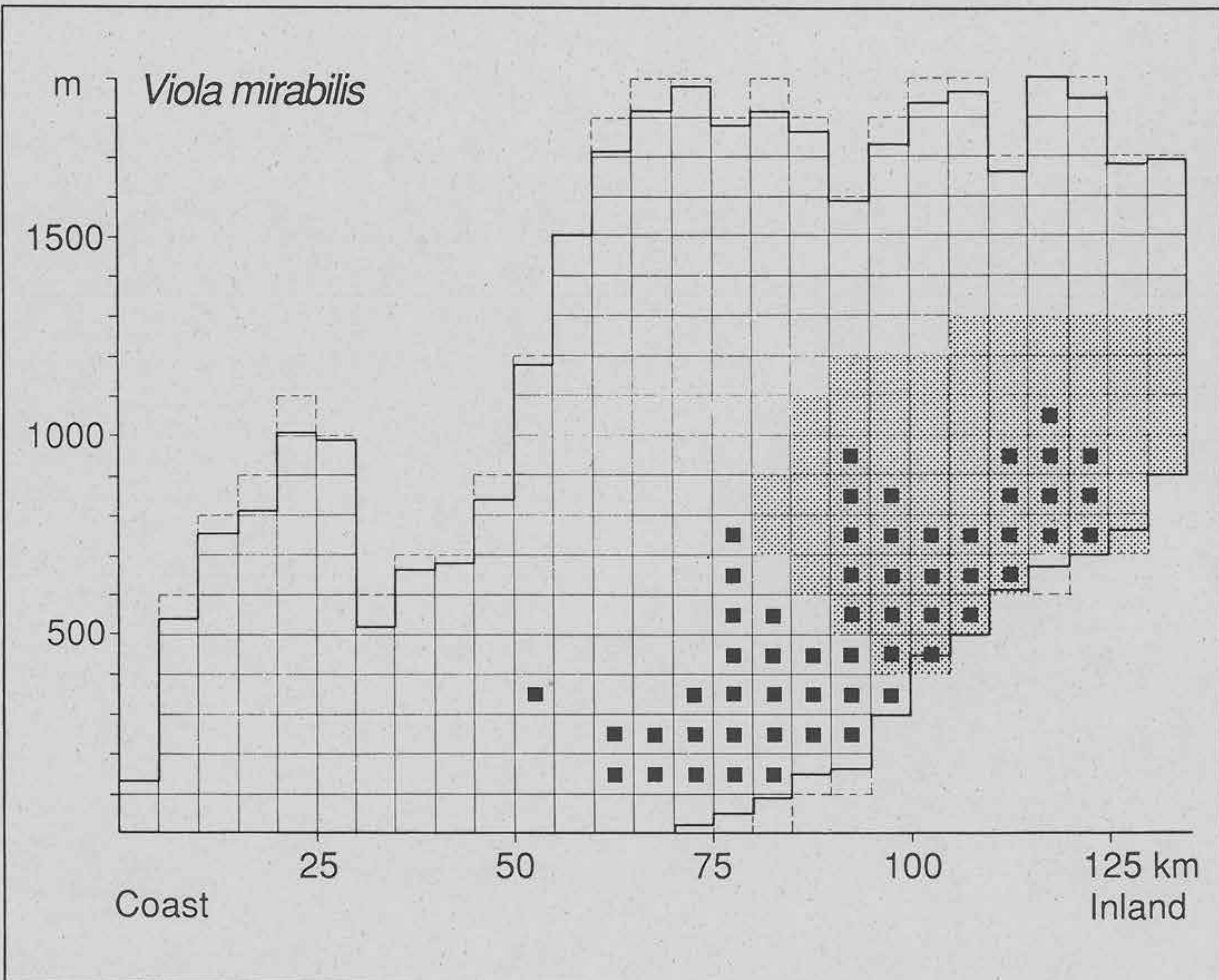


Figure 7b

Correlative models showing the current (■) and predicted (▒) vertical ranges of a: the coastal, frost-sensitive species Hypericum pulchrum *and b: the continental species* Viola mirabilis. *Both models are based on the Norwegian climate scenario, including a 2°C increase in summer temperature and a 4°C increase in winter temperature.*

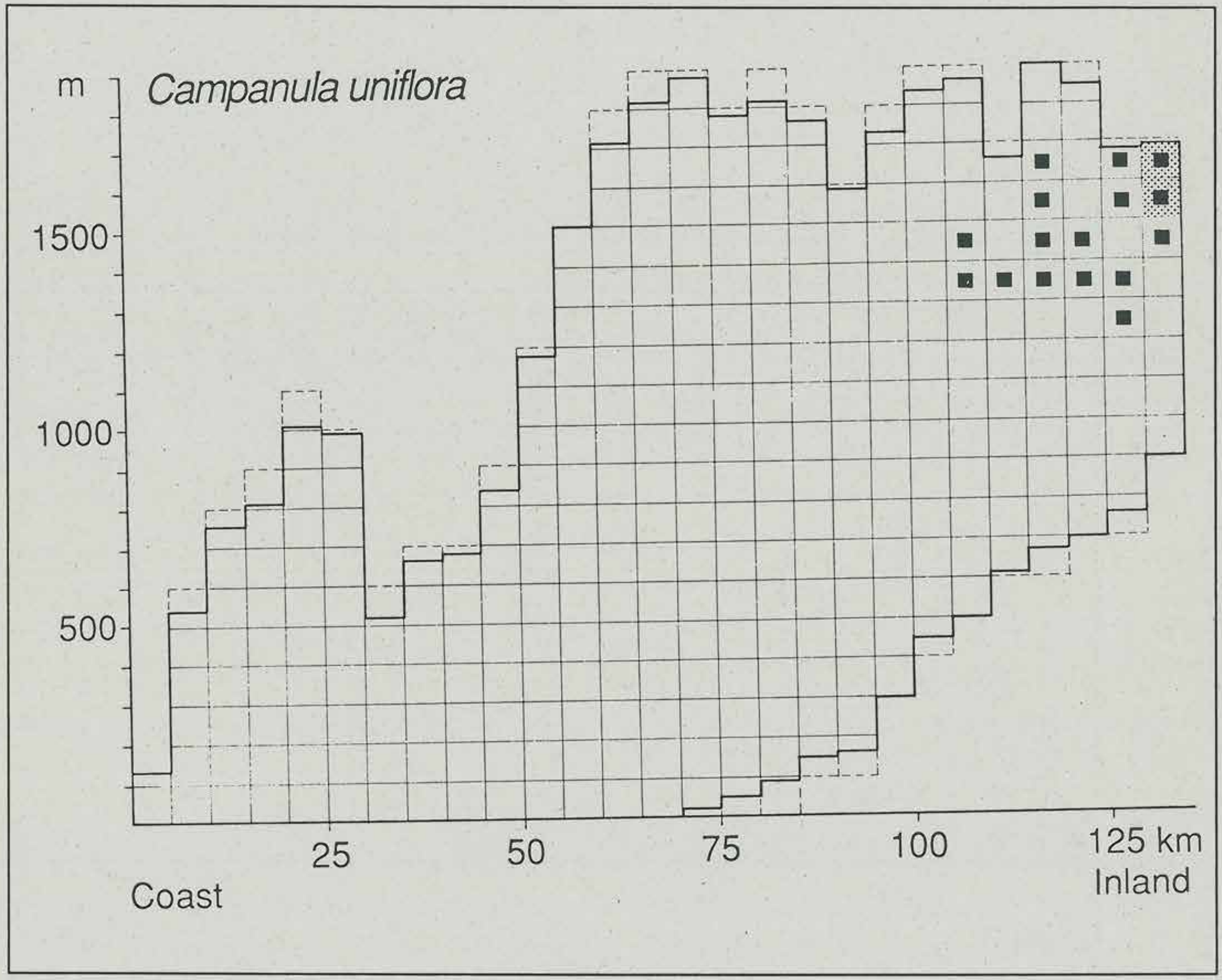


Figure 8
A correlative model of the vertical range of the rare middle alpine and continental species Campanula uniflora; *current distribution (■) and predicted distribution (░).*

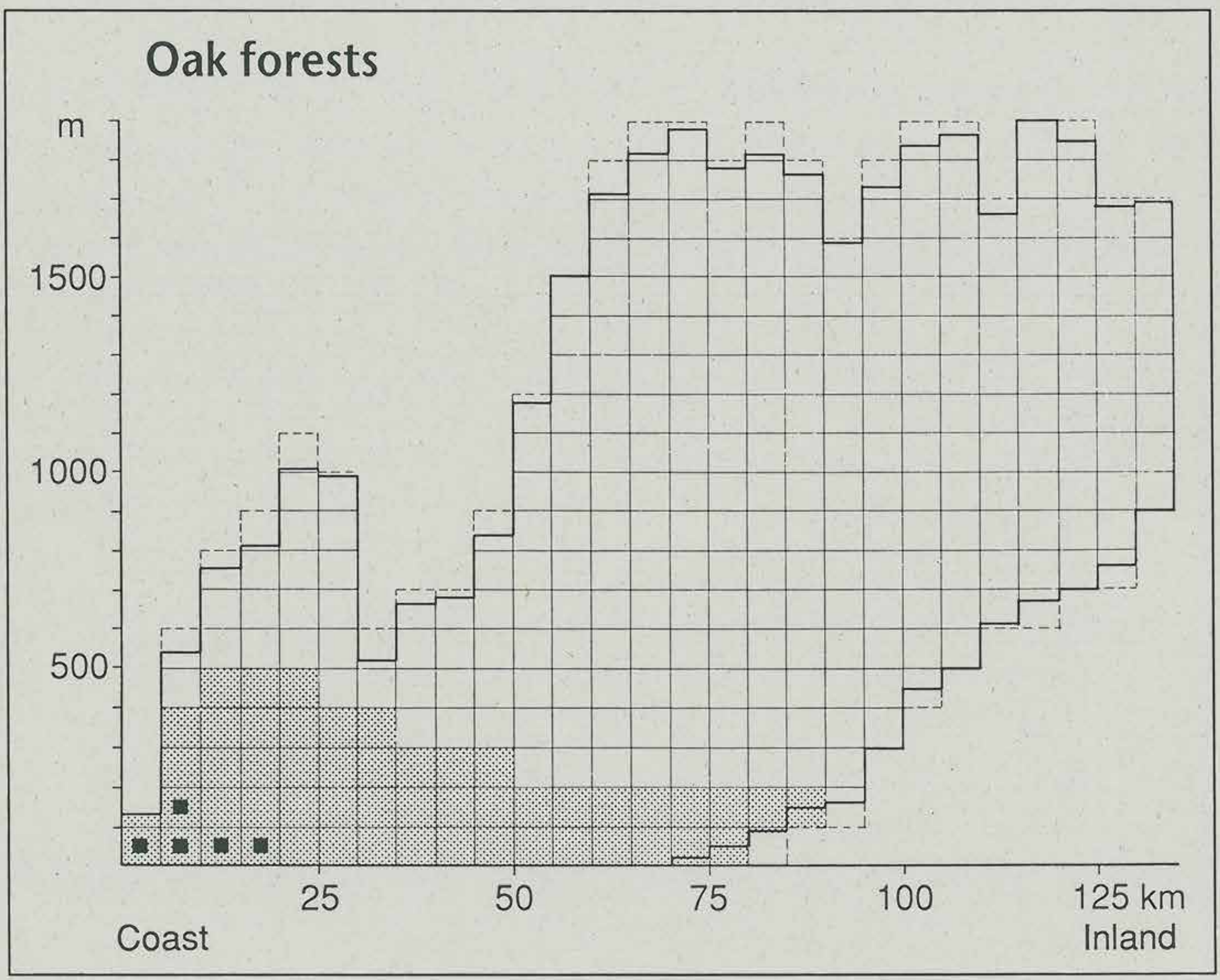


Figure 9a
Correlative models showing the current (■) and predicted (░) ranges of a: coastal oak forests and b: eastern and middle/northern boreal tall herb communities. Both models are derived from the most probable scenario for climate change in Norway.

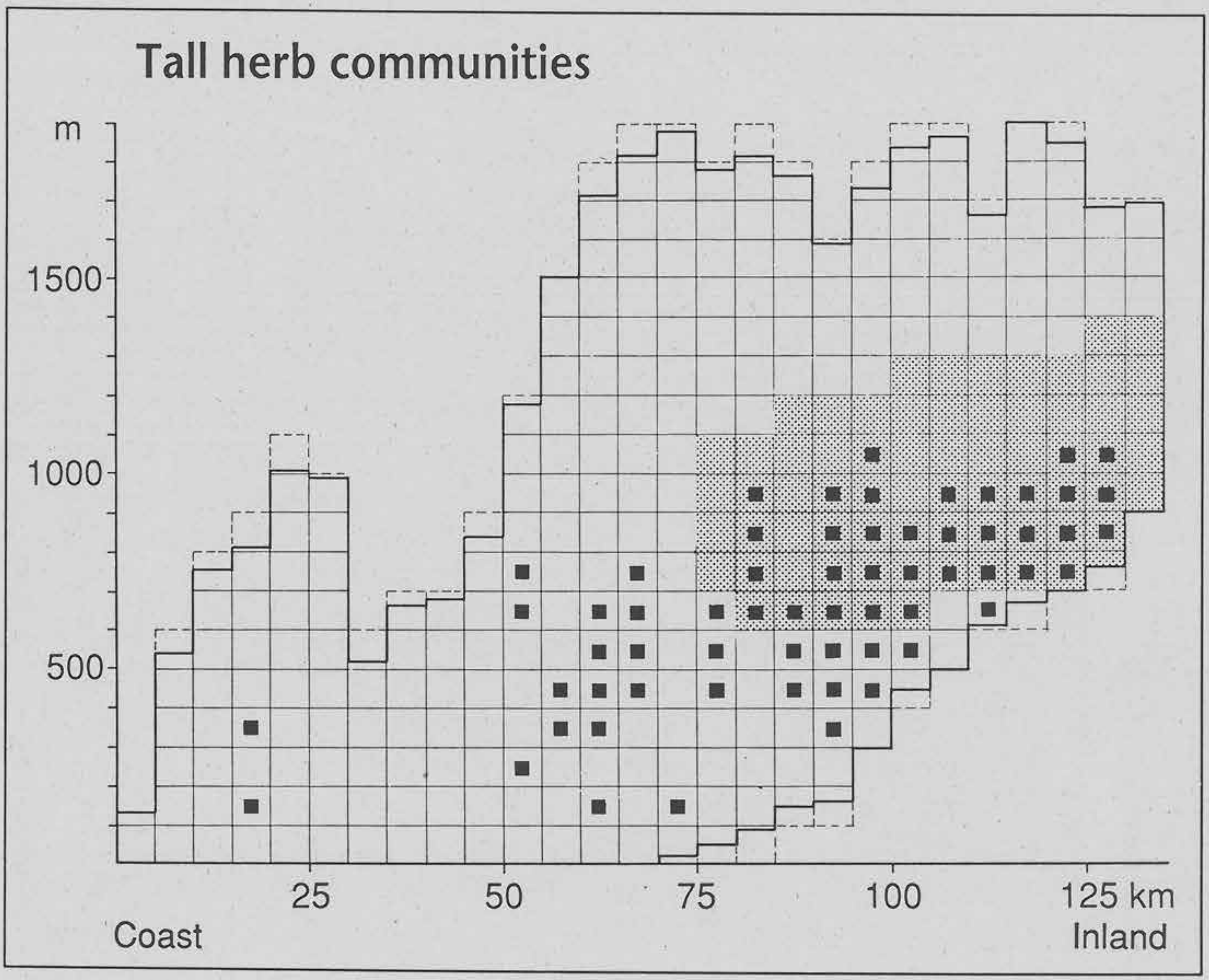


Figure 9b

Correlative models showing the current (■) and predicted (░) ranges of a: coastal oak forests and b: eastern and middle/northern boreal tall herb communities. Both models are derived from the most probable scenario for climate change in Norway.

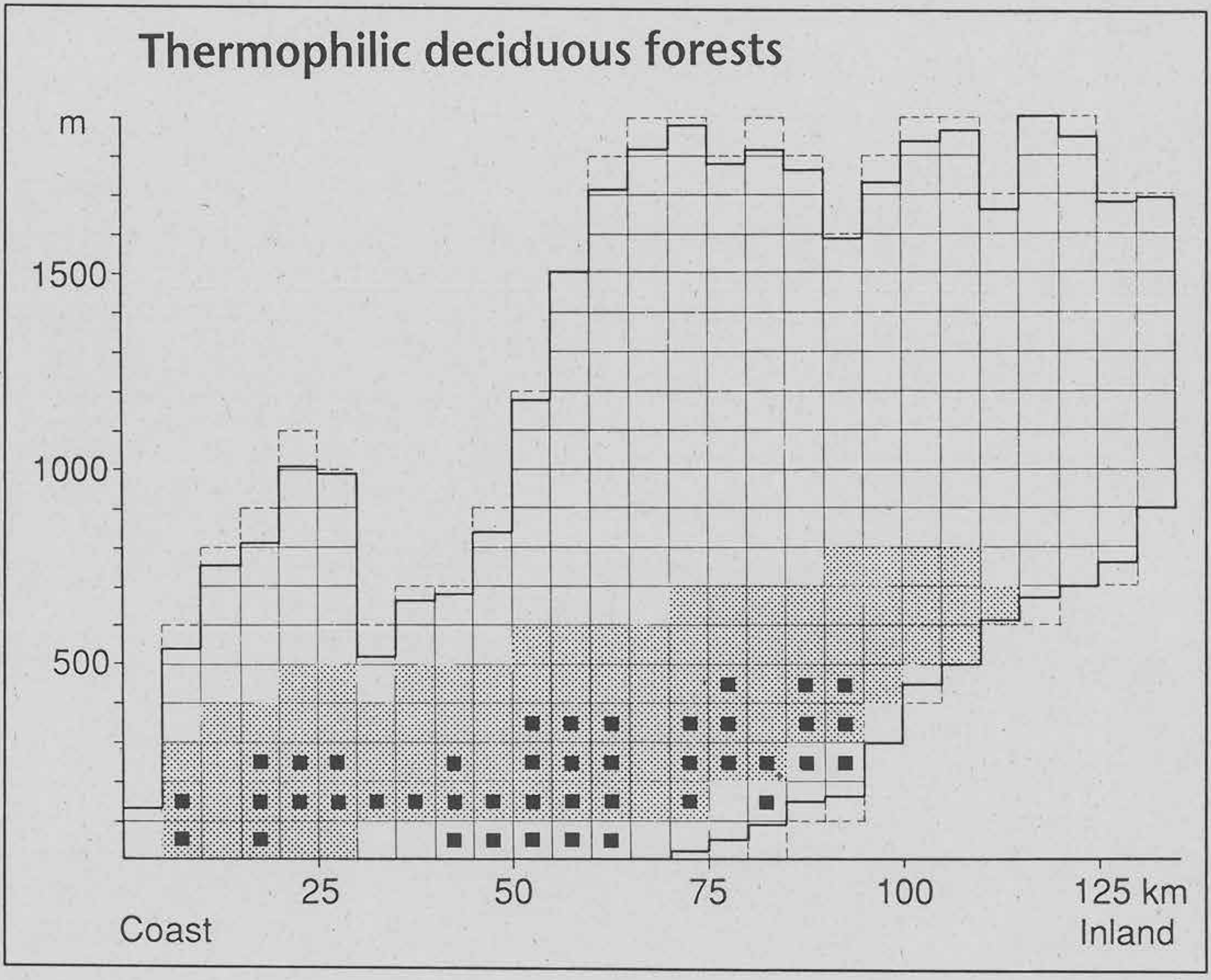


Figure 10a

Correlative models showing current (■) and predicted (░) vertical ranges of a: thermophilous Ulmus glabra-Corylus *forest and b:* Phyllodoce-Vaccinium myrtillus *heath. Both models are derived from the most probable scenario for climate change in Norway.*

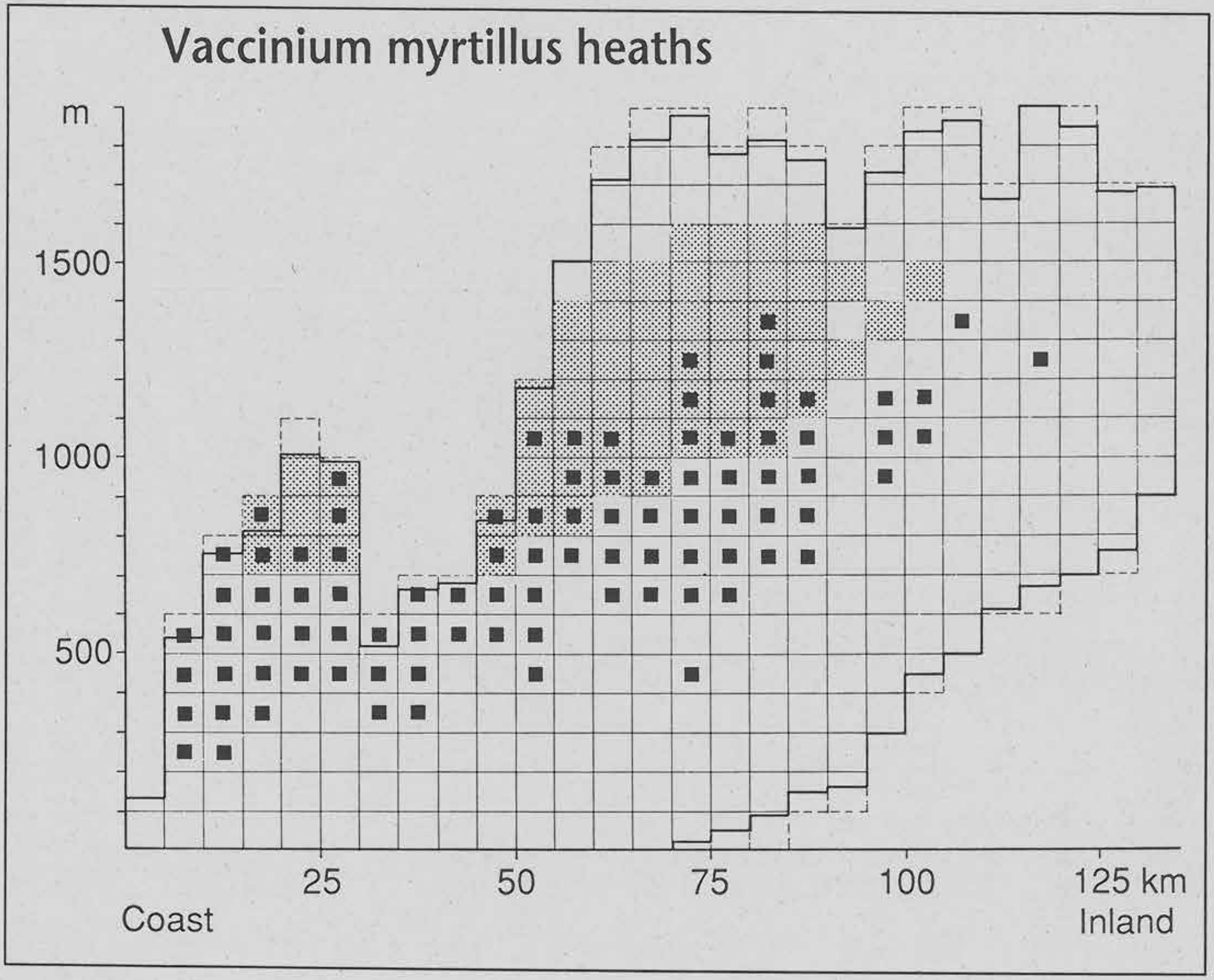


Figure 10b
Correlative models showing current (■) and predicted (▒) vertical ranges of a: thermophilous Ulmus glabra-Corylus *forest and b:* Phyllodoce-Vaccinium myrtillus *heath. Both models are derived from the most probable scenario for climate change in Norway.*

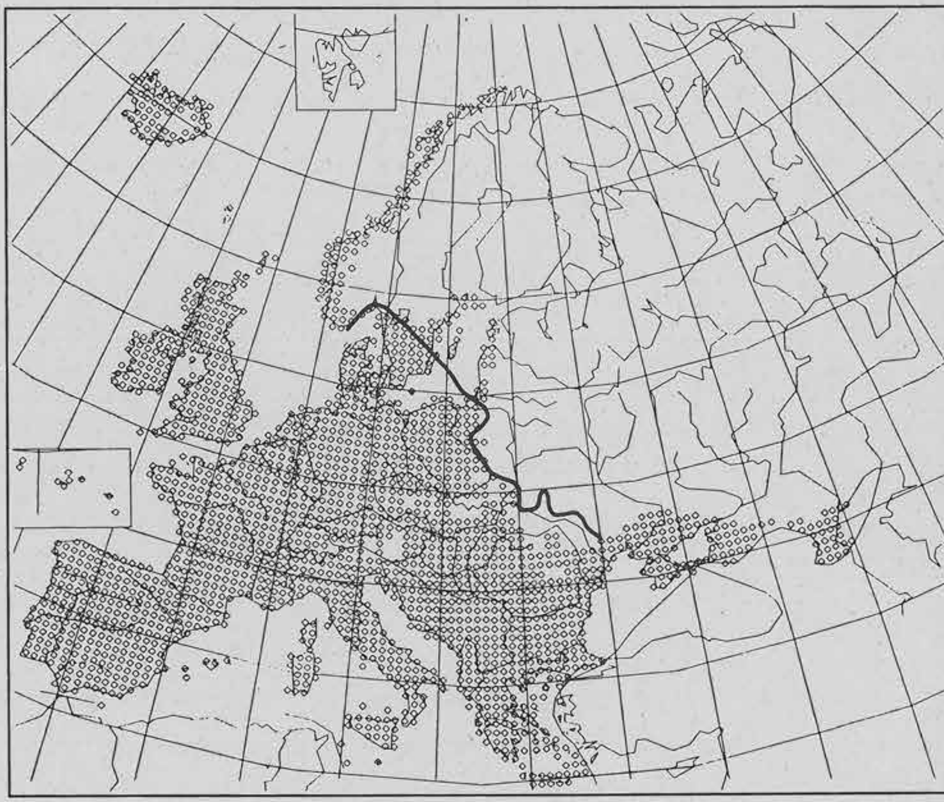


Figure 11a

The geographical distribution of Fagus sylvatica. *a: The current distribution in north-eastern and eastern Europe. The solid line indicates the lowermost points in the terrain where the mean temperature of the coldest month is -3°C. b: The potential distribution if winter temperatures increase by 4°C. After Dahl 1990.*

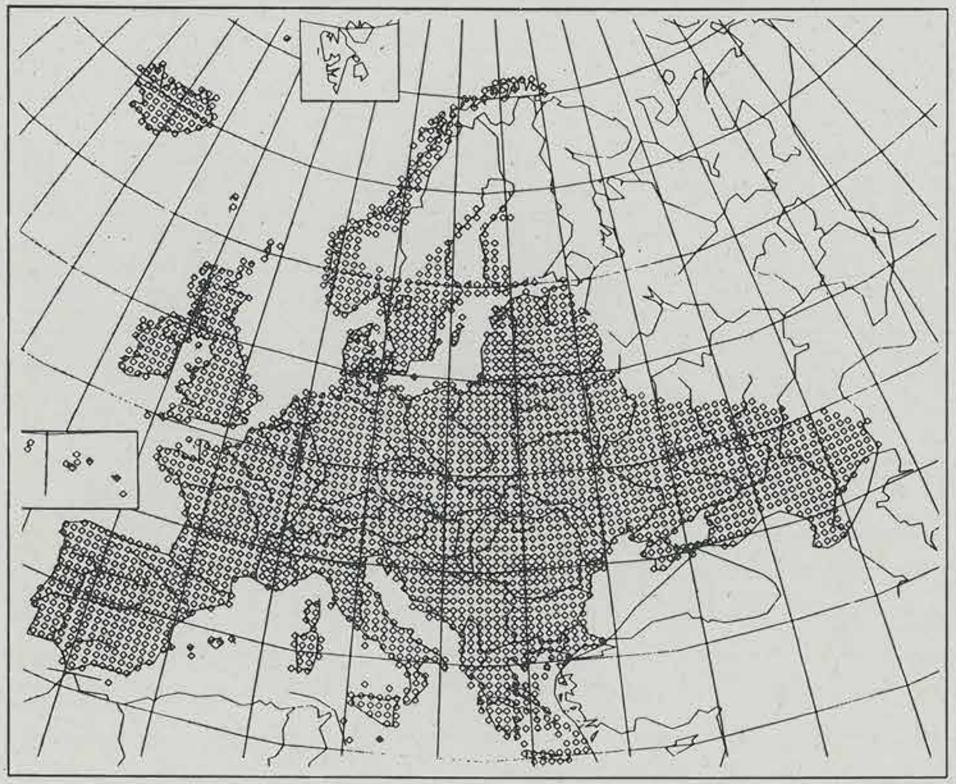


Figure 11b
The geographical distribution of Fagus sylvatica. *a: The current distribution in north-eastern and eastern Europe. The solid line indicates the lowermost points in the terrain where the mean temperature of the coldest month is -3°C. b: The potential distribution if winter temperatures increase by 4°C. After Dahl 1990.*

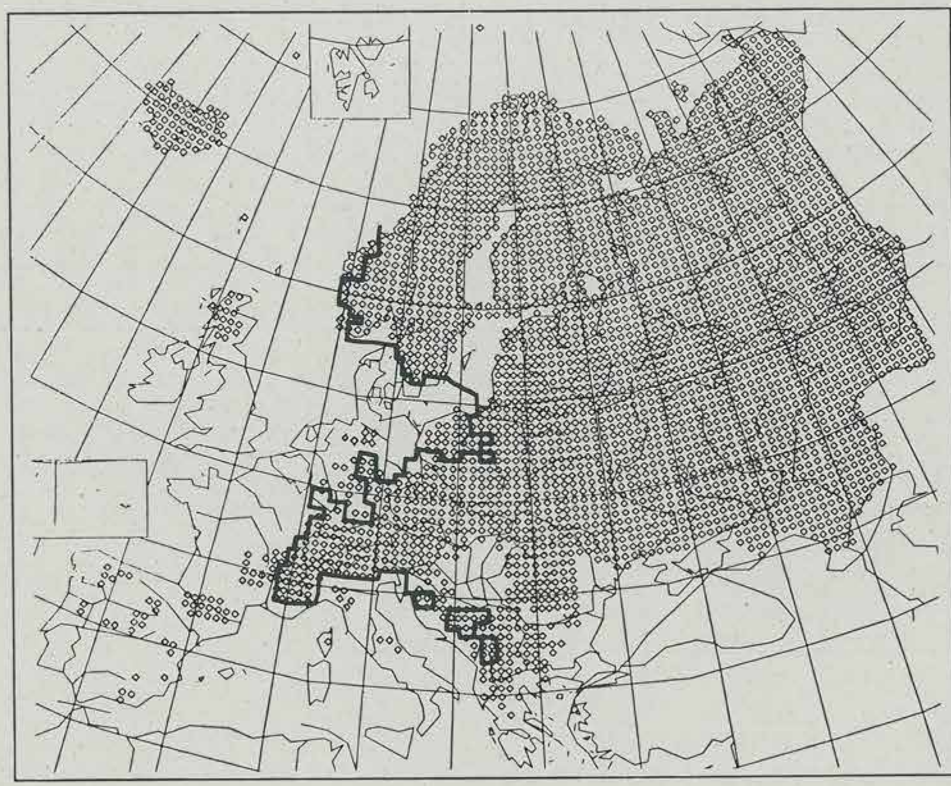


Figure 12a

The geographical distribution of Picea abies. *a: The current distribution in Europe. Areas to the east of the solid line have a mean temperature of lower than -2°C in the coldest month. b: The potential distribution if winter temperatures increase by 4°C. After Dahl 1990.*

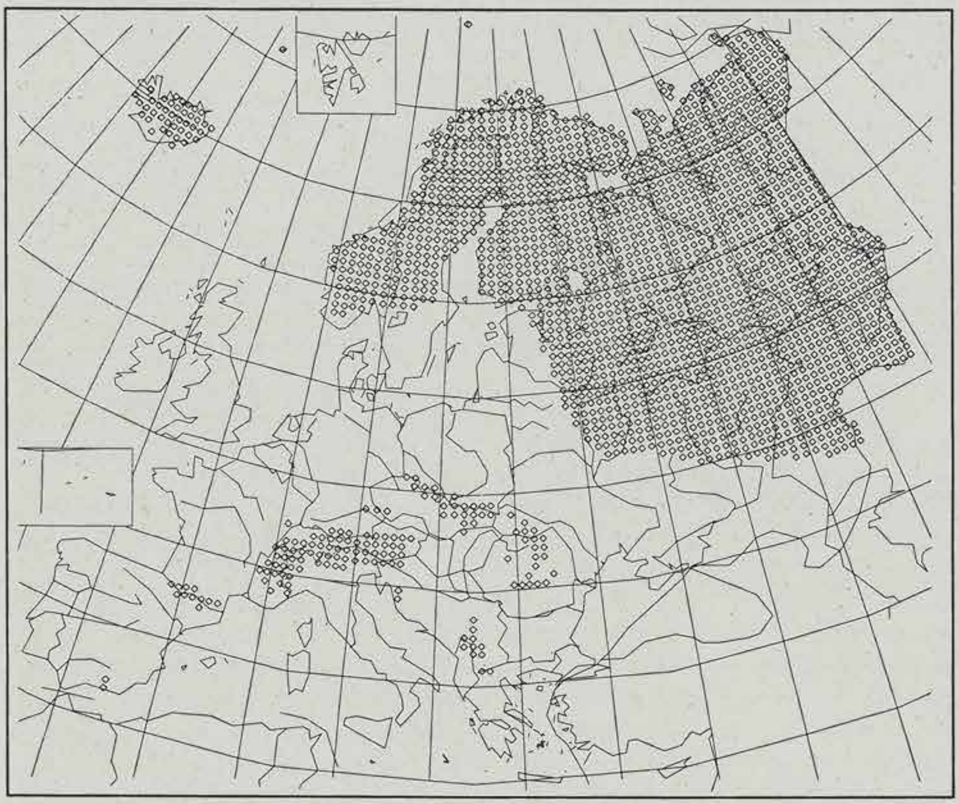


Figure 12b
The geographical distribution of Picea abies. *a: The current distribution in Europe. Areas to the east of the solid line have a mean temperature of lower than -2°C in the coldest month. b: The potential distribution if winter temperatures increase by 4°C. After Dahl 1990.*

6 Effects of climate change on the biodiversity of plant communities and rare species

6.1 Effects of climate change on the biodiversity of plant communities

We have no clear idea whether the changes in weather patterns will cause a general increase or general decrease in biodiversity. In order to know what the changes in biodiversity are going to be for any one community, we need to know the ratio of the number of species that will enter that community against the number of species that will leave it. We also need to know the relative abundance of each species and the age structure of the community. We do not have this basic information for any plant community.

Our lack of knowledge is apparent if we consider one of the major consequences of a change in the precipitation regime of Norway. In some areas, for example forests, which are predicted to become susceptible to an increase in major disturbance, be it landslide or fire, large gaps will be formed on a more or less regular basis. The succession of plants recolonising these gaps might be expected to follow a typical pattern. Annuals will be followed by herbaceous vegetation, followed by scrub, followed by trees. This will lead to an uneven age structure in the forest and this could be claimed to be an increase in biodiversity. However, if an extreme disturbance event occurs in an area with a high diversity of native plants, the recolonisation of the disturbed area is not likely to include all the species that were previously present. In other words, the biodiversity will decrease. The gaps may be recolonised by thermophilous species spreading from the south (Chapter 4), which will lead to an increase in biodiversity.

The pattern of recolonisation of gaps will also depend on their frequency and intensity. For example, a high frequency of fires is believed to have been a key process in the development of the forest tundra in Canada after the postglacial forest optimum (Sirois & Payette 1991).

6.2 Effects of climate change on rare species

Most rare species or those species considered threatened with extinction are not likely to be directly threatened by climate change. These species are more at risk from land-use changes which may or may not be due to climate change.

A rare species, like any other, can either move with the climate or adapt to the new climate. Many species have the ability to adapt to changes in their environment because they have a substantial gene pool. Populations which become small or fragmented may lose important genes by genetic drift (Bradshaw & McNeilly 1991) and become unable to adapt to the changes imposed on them, and consequently become extinct.

Rare species will also be threatened with extinction if they are removed by a physical disturbance. The probability of the patch of ground occupied by an individual of a rare species being disturbed is generally very low. The chance of a single rare tree in a forest being the one tree that is struck by lightning gives a very simple analogy. The probability of a rare species being disturbed also depends on its life history strategy. The chance of the rare tree being struck by lightning is greatly increased if it is taller than all the other trees. Populations of annual species could become extinct if they have one catastrophic season and have no long-term seed bank (Silvertown 1989). The threat to rare species also depends on whether they exist in rare or common habitats. Turner et al. (1989) have demonstrated with some elegant simulation models that rare habitats will be more susceptible to extinction if there are frequent disturbances, whereas in more common habitats it is high intensity disturbances which will have the greatest effect.

A rare perennial species which normally only reproduces vegetatively, i.e. has restricted gene flow and migration ability, and lives in only a few isolated areas which are likely to be frequently disturbed has a higher probability of becoming extinct than any other life-history group.

We have compiled a table (**Table 2**) summarising the information we have about species that are rare in Norway. 12 species (*Poa stricta*, *Luzula arctica*, *Stellaria crassipes*, *Taraxacum dovrense*, *Campanula uniflora*, *Zannichellia palustris*, *Butomus umbellatus*, *Moehringia lateriflora*, *Melandrium angustifolium*, *Silene tatarica*, *Saxifraga hirculus* and *Hippuris tetraphylla*) are definitely threatened with extinction in Norway. 8 other species

Table 2 *The characteristics of some rare species of southern Norway (list from Høiland 1990) and northern Norway (list from Høiland 1986) categorised in Column 1 by community (Fremstad & Elven 1987). In Column 2 we have made an estimate of the abundance of the community in Norway, 2: very common, 3: common, 4: scarce, 5: rare. In Column 3 we have made an estimate of the degree to which the communities are going to be affected by the predicted changes in climate and hydrology and also by disturbance resulting from these changes, 0: no change, 1: little change, 2: substantial change, 3: under threat of disappearance. In Column 4 we have listed the causes of the changes that are most likely in the communities, Sc: snow cover, H: hydrological factors (unspecified), e: erosion, s: sedimentation, m: solifluction/mass movement, F: fire, D: drought, L: sea-level rise, T: temperature increase. Column 5 lists the factors causing the decline of species in northern Norway (from Høiland 1986), 1: development, 2: dumping (roadside, wasteheaps, etc.), 3: fence building along rivers, 4: regulation of watercourses, 5: agriculture, 6: overgrazing, 7: cutting, 8: afforestation, 9: shading (caused by cessation of grazing), 10: pollution, 11: plant collecting, 12: decline due to natural fluctuation of population size. Column 6 gives the life-history of each species, A: annual, P: perennial, S: shrub, T: tree. In Column 7 we have given an indication of seed size and the method of dispersal, 1: very light seeds travelling great distances on the wind, 2: heavier wind-dispersed seeds, 3: large seeds likely to fall very close to the parent, 4: seeds eaten or taken by animals and deposited away from the parent.*

Southern Norway	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Poa stricta	R3b	5	3	Sc		P	2
Phippsia concinna	T7c	4	1	Sc		P	2
Scirpus pumilus	(G/M)	4	2	H		P	2
Carex arctogena	R3a	4	0-1	-		P	2
Carex bicolor	Q	4	1-2	e,s		P	2
Luzula arctica	R7	5	3	Sc,m		P	2
Stellaria crassipes	R7	5	3	Sc,m		P	1,2
Papaver radicatum							
ssp. *relictum*	F1	4	0-1	-		P	1
ssp. *intermedium*	F1	4	0-1	-		P	1
ssp. *gjaerevolli*	F1	4	0-1	-		P	1
ssp. *groevudalense*	F1	4	0-1	-		P	1
ssp. *oeksendalense*	F1	4	0-1	-		P	1
Draba cacuminum	(R3)	4	0-1	-		P	2,3
Braya linearis	F1	5	1	-		P	1,2
Saxifraga paniculata	(F2)	3	1	-		P	2
Saxifraga opdalensis	(T7)	4	1	Sc		P	2
Taraxacum dovrense	(R7)	5	3	Sc,m		P	1
Campanula uniflora	R3b	5	3	Sc		P	2

Northern Norway	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Picea abies ssp. *obovata*	A	3	1-2	F		T	1,3,4
Potamogeton rutilus	(P4)	(3)	2	D		P	2
Potamogeton vaginatus	(P4)	(3)	1-2	D		P	2
Zannichellia palustris	X1c	4	2-3	L	10	P	2
Butomus umbellatus	(O5)	3	3	H		P	2,4
Alopecurus arundinaceus	(X9)	3	0-1	L		P	2
Calamagrostis chalybaea	C2c	4	2	Sc	2	P	2
Arctagrostis latifolia	(L,M)	(3)	-	-		P	2
Trisetum subalpestre	Q	3	1-2	H	4	P	2
Arctophila fulva	(O/P)	(3)	1-2	L,H	10	P	2
Roegneria fibrosa	Q	3-4	1-2	H	3	P	2

(Table 2 cont.)

Northern Norway	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Scirpus pumilus	(G/M)	4	2	H	1	P	2
Eriophorum gracile	M2-M4	4	1-2	H,D	12	P	2,3
Carex scirpoidea	T	(3)	1	Sc		P	2
Carex lapponica	M2-M3	4	2	T	9	P	2
Carex disperma	E	3-4	1	H	12	P	2
Carex stylosa	G	(3)	1	-		P	2
Cypripedium calceolus	B2	5	1	F		P	1
Nigritella nigra	(M3)	5	1-2	H,D		P	1
Platanthera oligantha	R3-R4	4	1	-	6,11,12	P	1
Arenaria humifusa	F6	5	0-1	-	1	P	1,2
Arenaria pseudofrigida	F1	5	0-1	-		P	1,2
Moehringia lateriflora	E	(3)	2-3	H,T	1,4	A	1,2
Stellaria crassipes	R7	5	3	Sc,m	11	P	1,2
Cerastium diffusum	(W5)	3	1	-		A	1,2
Melandrium angustifolium	Q	3-4	2-3	H,T	12	P	1,2
Silene tatarica	(Q)	3	2-3	H,T	5,6	P	1,2
Ranunculus lapponicus		4	2	H,D	1,4	P	2,3
Thalictrum rariflorum	G	3	1	-	4	P	1,2
Papaver lapponicum	F1	4	0-1	-	2,9,11	P	1
Papaver laestadianum	F1	4	0-1	-	4	P	1
Papaver dahlianum	F1	4	0-1	-	3,11	P	1
Papaver radicatum							
ssp. *subglobosum*	F1	4	0-1	-	9,11	P	1
ssp. *hyperboreum*	F1	4	0-1	-	6	P	1
Draba cinerea	(F1)	4	0-1	-		P	2
Isatis tinctoria	(G)	3	0	-	12	B	2,3
Braya purpurascens	R3	5	0	-		P	2
Rorippa islandica	G	2	0	-	1,9	A	2
Saxifraga hirculus	M	3-4	2-3	H,D,T		P	2
Saxifraga paniculata	(F2)	3	1	-		P	2
Ribes nigrum	(E)	3	0	-	1,4,7	S	3,4
Sorbus neglecta	B1	3-4	0-1	-		S	3,4
Genista tinctoria	H1-G	3	0	-		S	3,4
Oxytropis deflexa							
ssp. *norvegica*	(F1)	5	2	T		P	3,4
Hippuris tetraphylla	(X4)	5	2-3	L	1	P	3,4
Polemonium boreale	(U5-G)	3-4	2	T		P	2
Mimulus guttatus	G	2-3	0	-	1,9	A	2
Galium pumilum							
ssp. *normanii*	(R3-H)5	0	-	5,8	P	3,4	
Senecio integrifolius	(R3)	5	2	T	1,6	P	2
Crepis multicaulis *	(S1)				9,11	P	2

* = probably extinct

in Høiland's list of rare species, are predicted to experience substantial change those are: *Scirpus pumilus* , *Potamogeton rutilus*, *Calamagrostis chalybaea*, *Carex lapponica*, *Ranunculus lapponicus*, *Oxytropis deflexa* ssp. *norvegica*, *Polemonium boreale*, *Senecio intgrifolius*, *Crepis multicaulis* may already be extinct. Other rare species (*Isatis tinctoria*, *Braya purpurascens*, *Rorippa islandica*, *Ribes nigrum*, *Genista tinctoria*, *Mimulus guttatus* and *Galium pumilum* are not apparently threatened by climate change and may indeed become more common. The remaining species may be affected, but it is difficult to predict the effects on the size of their populations without undertaking detailed population dynamics studies.

7 Research and monitoring needs

7.1 Research needs

7.1.1 General

A general lack of ecological knowledge is probably the main reason for the greatest uncertainties in our ecological impact scenarios. It is difficult to determine what the main gaps in our knowledge are. However, discussions between European ecologists have indicated three main ones:
- migration rates of species
- establishment of species
- ecosystem sensitivity

To fill the gaps, we need an intense and probably costly international research effort over the next few years. Much activity will be concentrated on monitoring, population dynamics of plant and animal species, experimentation and modelling. No doubt the ecological research community will also be faced with many challenges as regards the structure and organisation of this research effort.

We will classify the various research approaches into three main groups (see below).

7.1.2 Observation/monitoring

This is the descriptive group of approaches. Long-term systematic, standardised and yearly observations at the same location and on the same plot will no doubt provide greatly needed data sets on changes and fluctuations in plant and animal populations. These data sets from the various monitoring programmes will be quite indispensable if we are to understand the dynamics of species and ecosystems. However, because we have little knowledge about the demography of many important species, this monitoring should perhaps last for many decades if it is to provide the results required for feeding into dynamic models (see below).

We propose that most of the demographic studies on important species (e.g. tree species) and some rare species, both plants and animals, should be concentrated on typical ecotonal boundaries. This depends on the following hypothesis:

Ecotones are areas that are particularly sensitive to climate change as they represent marginal localities or areas for many species due to a steep climatic or other type of abiotic gradient.

Well known ecotones are:
- the alpine timberline
- the forest-tundra ecotone
- the forest-steppe ecotone
- the savanna-steppe ecotone
- the steppe-desert ecotone

Ecotones of a more local nature are found along the snow bed-ridge gradient in the mountains in boreal regions. The snow bed-ridge ecotone should be particularly sensitive to changes in the snow cover, including its pattern (influenced by wind direction), depth and duration.

Ecotones should be equally important for research and monitoring. A general design for ecotonal research and monitoring is outlined in **Figure 13 A & B**. Ecotones in sloping countryside (alpine timberline, snow bed-ridge ecotone) will constitute shorter transects (300-800 m) compared with ecotones in flatter countryside (10-100 km) such as steppe areas in southeastern Europe and prairie districts in North America. However, they will be equally important as they will respond to different climatic parameters. The snow bed-ridge ecotone will be susceptible to changes in both wind direction, and temperature and precipitation regimes. The alpine and arctic timberlines will mainly respond to changes in the thermic regime. The forest-steppe ecotone will respond to changes in the precipitation and hydrological regimes because drought is the main factor limiting the trees and other species from invading the drier steppe and prairie districts.

In Norway and other mountainous countries, we should also place ecotonal transects for research and monitoring across main river valleys because major ecological changes (see Chapter 4) can take place there due to hydrological changes, erosion and sedimentation.

Autecological studies. Thorough autecological studies on important indicator species should be carried out along both short and long vertical transects. These studies should be accompanied by systematic mapping of the distribution of the same species, using a grid system. The vertical transects that are chosen should preferably be located in areas with high _ diversity and steep climatic gradients, e.g. in the western United States and Canada (British Colombia), western Norway, Scotland, the west-

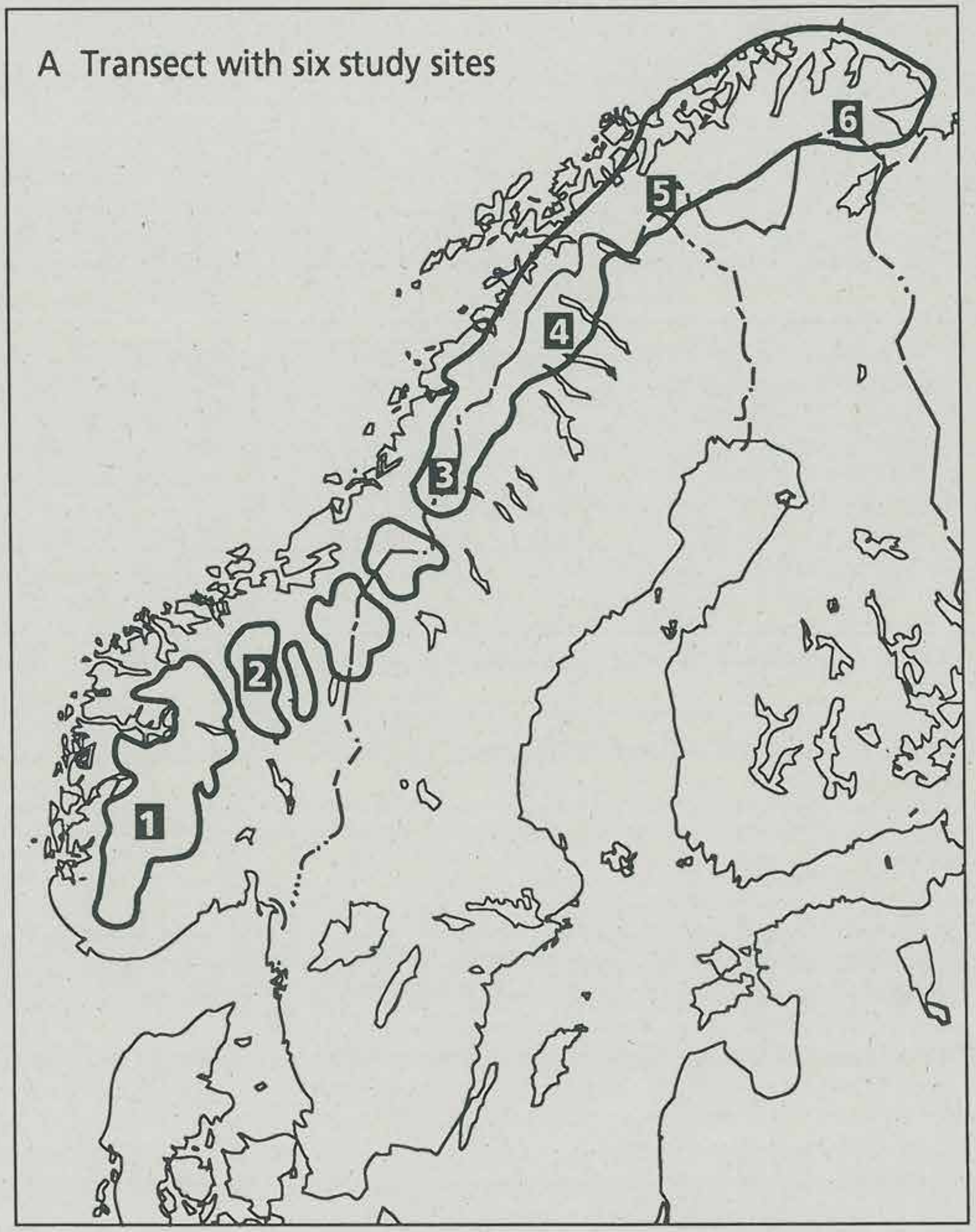


Figure 13a
A possible general design for monitoring population processes along a three-tier transect. The example given here shows how the system could be applied to investigate sensitive ecotones. The ecotone chosen for the example, the boreal-alpine ecotone, is one of several that could be investigated in this way. a: A transect of the Norwegian Scandes range showing six possible locations of study sites. b: Each of the six sites would consist of a second-tier transect across a mountain side with five sampling points at, for example, 500 m intervals. At each of these intervals there would be a third- tier transect consisting of five groups of five permanent quadrats at intervals of 50 m altitude around the treeline, for example.

ern Alps and Japan. In some of the transects where a great deal of research and monitoring effort are allocated, it may be useful to establish automatic meteorological recording stations. The autecological approach is probably important since species respond individually to ecological factors. The responses of the species will therefore be decisive for what will happen to the floristic composition of the specific plant community.

Phenological studies. Phenological studies can be associated with both specific autecological transect studies and fairly large geographical areas. The choice of species for phenological studies must be discussed. Wide-ranging species are probably the best ones for phenological 'monitoring', and they should be genetically fairly homogeneous. For east-west comparisons (Eurasia-North America) in the arctic, boreal and northern temperate

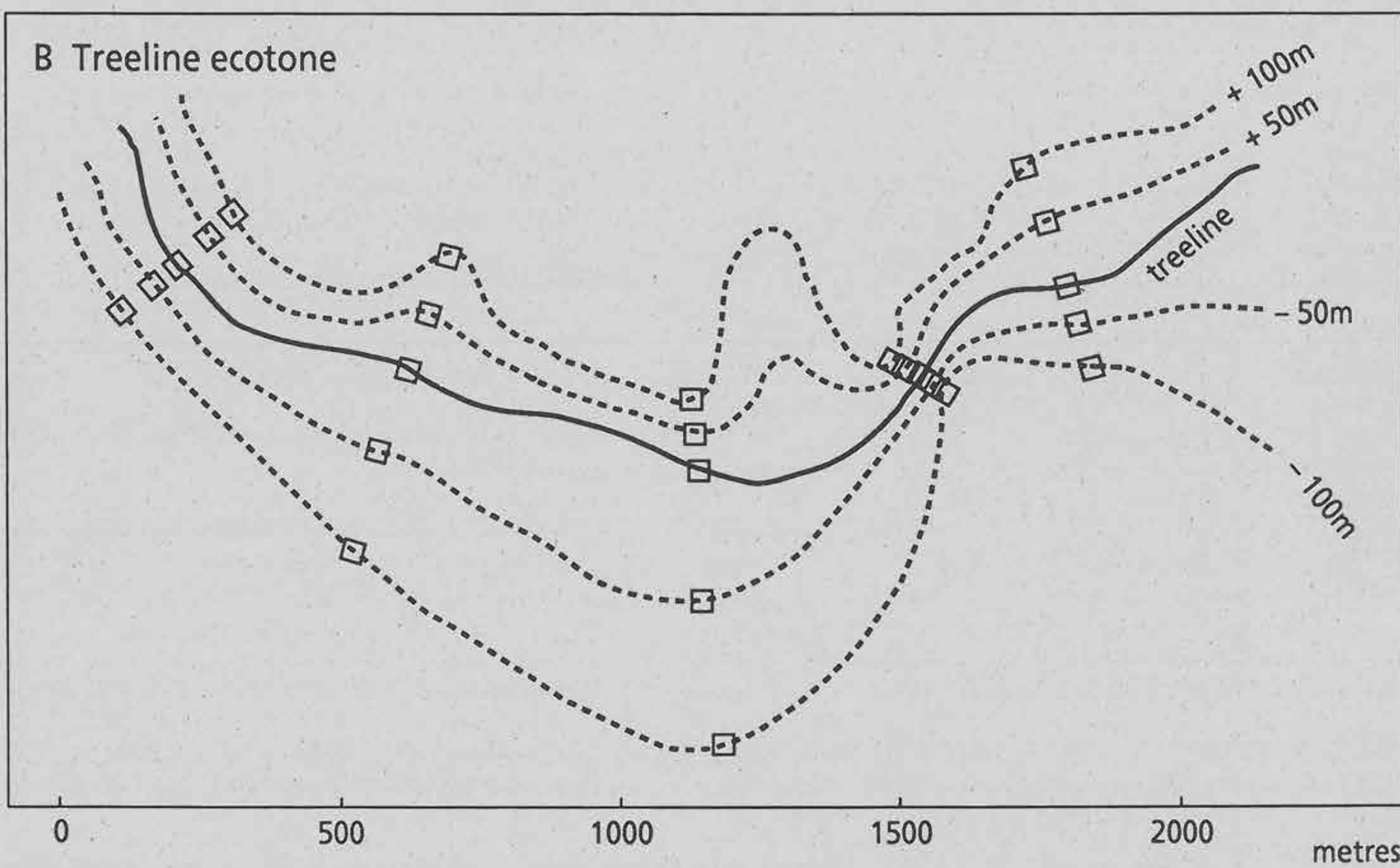


Figure 13b
A possible general design for monitoring population processes along a three-tier transect. The example given here shows how the system could be applied to investigate sensitive ecotones. The ecotone chosen for the example, the boreal-alpine ecotone, is one of several that could be investigated in this way. a: A transect of the Norwegian Scandes range showing six possible locations of study sites. b: Each of the six sites would consist of a second-tier transect across a mountain side with five sampling points at, for example, 500 m intervals. At each of these intervals there would be a third- tier transect consisting of five groups of five permanent quadrats at intervals of 50 m altitude around the treeline, for example.

zone, a lot of circumboreal and circumarctic species may serve as candidates, for example *Potentilla palustris*, *Galium boreale* and *Rubus chamaemorus*.

Existing data sets. Existing data sets on distribution, e.g. from various atlases, will constitute an important fundament for future modelling and ecological predictions. However, most of these data sets are not gridded and therefore are not very useful for modelling purposes. Atlas Flora Europaea (AFE) (Tutin et al. 1965-90) contains gridded distributional data for about 20% of the European vascular plant flora, i.e. about 1000 species. The grid cell size is 50 x 50 km. A climate data base is linked to the same grid system. As a separate, cooperative European project, the distribution of some important ecological indicators recorded in AFE will be digitised and, together with the climate data base, become the fundament for a correlative model of distribution patterns brought about by climate change.

An important task in the near future will be to digitise and grid distributional data from various atlases, both on national (Norway), regional (Europe) and global scales. A survey of relevant atlases should be made and the optimal grid cell size should be discussed.

7.1.3 Experimentation

This is the second group of approaches required to learn the major causes of change. Experimentation will be important if we are to understand ecological processes and the cause-effect relationships in the ecosystems. If we do not understand the causes of ecosystem processes we will never obtain reliable ecological scenarios (draft report of GCTE focus 2 meeting in Trondheim, June 1991).

In situ experiments. To give us an understanding of ecosystem processes and how the ecosystem functions, various manipulation techniques will need to be devised for use in field experiments. These may be expensive. They can be performed at several organisational levels in the ecosystem - at species, population and plant community levels:

- **Transplantation/genetical experiments**
  Transplantation techniques may be used to expose organisms to various climatic stresses. A transplant represents a translocation of species or pieces of intact vegetation along climatic gradients. A transplantation experiment along an east-west gradient transect in central Norway started in the summer of 1991, organised by the Norwegian Institute for Nature Research (NINA) and the University of Trondheim (UNIT). About 50 intact vegetation mats (each 1.2 m^2) are being moved across vegetation zones (from low alpine to southern boreal and vice versa) and oceanicity sections (from winter-cold to winter-mild areas and vice versa). Changes in the presence and absence of species in 16 smaller quadrants in each plot are the essential parameters being recorded. Demographic studies on important species are being carried out each summer.

  Transplantation experiments along a south-north gradient, e.g. in Scandinavia, will provide a great deal of information about the influence of day-length on the growth and vitality of species. Such experiments have already been carried out using *Betula pubescens* and certain grass species (Håbjørg 1978).

- **Greenhouses**
  Experimental technology using greenhouses constitutes a group of approaches that are relevant for climate-change research. Small greenhouses may be located in intact vegetation and stress can be applied through various concentrations of $CO3$ or temperature (Oechel & Strain 1985).

- **Soil warming techniques**
  Soil warming techniques are interesting both from the point of view of impact on soil properties, including decomposition of organic matter, nitrification and mineralisation, and for various vegetation and plant population parameters. The soil warming technique has already been taken into use by the Unit of Comparative Plant Ecology at Sheffield University (Professor P. Grime's group). A variety of soil warming techniques adapted to various regions and ecosystems should be further developed.

- **Measuring dispersal and migration rates**
  Such experiments will probably require advanced technology and carefully chosen design. They will certainly be difficult to perform, but some attempt should be made.

  Well-planned and well-designed experiments can help us to a better understanding of:

  - the importance of extreme weather events (drought, late frost) on plant populations and vegetation, since many ecological disturbances (forest fires, floods and landslides) may be brought about by such extreme events

  - the importance of dispersal barriers (natural and cultural) and landscape fragmentation for the ability of species to shift their location in a changing climate (e.g. for the possible migration of temperate central European species northwards to Scandinavia)

  - the influence of climate change on soil processes (rates and directions of change):
    - decomposition of organic matter
    - mineralisation
    - nitrification
    - weathering

7.1.4 Modelling (see Baadsvik & Schei 1991)

Correlative models. A correlative approach may be used to compare the present distribution of species with climatic factors in order to identify the variables that must affect their range. This information can be used directly to produce correlative models, and the correlations can be used to predict the range of the species under new climatic conditions (Dahl 1990, Holten 1990a). In the case of Europe, the correlative approach may become very important because in this region (east to the Ural Mountains) we have the excellent distributional data base provided by Atlas Flora Europaea (AFE) (Tutin et al. 1965-90).
Dynamic models. The reliability of the outputs from dynamic

Dynamic models. The reliability of the outputs from dynamic models will depend to a great extent upon how much we know about the autecology and dynamics of the species and populations included. So far this basic knowledge is too inadequate.

7.1.5 Structure and organisation of research

Those aspects of integrated monitoring programmes that have to do with ecological monitoring should, in principle, be administered together with research (see modelling, below).

The administrative body for the global research effort on impact of climate change on natural terrestrial ecosystems should be located to the axis ICSU - IGBP - GCTE. The structure, including regionalisation of research activities, outlined in the START initiative (Eddy et al. 1991), should be further evaluated.

7.1.6 Recommendations

The 'ecological impact' sector of the research community should have the following flag activities for the next 1-5 years:

- establish **regional research programmes** perhaps using the CONNECT system as a template for cooperation (comment: CONNECT is a cooperative initiative between applied environmental research institutes in some central and northern European countries, including the United Kingdom, Germany, Belgium, the Netherlands, Denmark, Finland and Norway)
- establish a global **network** of research and monitoring sites
- **digitise/grid** existing distributional data for species (e.g. AFE) and plant communities (e.g. the Vegetation Map of Europe) (Noirfalise 1987)
- establish gridded national, regional and global data bases for the distribution of species, plant communities and ecosystems (biomes), and plot climatic parameters on the same grid.

7.2 Monitoring needs

7.2.1 General

We need many more long-term biological data sets if we are to make more reliable ecological scenarios in natural terrestrial ecosystems. So far, the biological parameters that are being monitored in various programmes are fairly general, reflecting the general vitality of species and not to any significant degree directly related to the disturbance factor concerned (acidification, eutrophication). However, the ecological monitoring that is being planned should answer both general and specific questions about changing ecological conditions.

Integration of ecological monitoring with parallel monitoring in the physical sciences is important. The ecological monitoring related to climate change should be carried out on various levels:

Intensive level. This is the biome level. Intensively monitored sites should be well equipped and have the following qualities and range of parameters:

- a wide range of general and specific biological parameters
- a complete weather station
- hydrological gauging
- high _ diversity, i.e. the topographical diversity, climatic diversity and, therefore, the biodiversity should be large
- little cultural disturbance
- quite strict protection
- easy access
- accommodation and laboratory facilities in the vicinity

The monitoring site on the biome level (e.g. arctic or alpine) should cover a great geographical area and also be a field site for intensive research (see above) and household international research teams for fairly long periods.

Norway should perhaps establish 2 or 3 intensive ecological monitoring sites covering the temperate, boreal, alpine and arctic biomes, of which the boreal and arctic ones should perhaps have priority.

Extensive level. This is the less expensive level. It covers a variety of regional climatic gradients with various temperature and moisture regimes. Extensive ecological monitoring should satisfy the following demands:

- monitoring of general biological parameters (wide-ranging species, community structure in permanent plots)
- weather station in the vicinity
- less strict area protection can be tolerated
- more cultural disturbance can be tolerated.

The remote sensing level. The changes in the earth's ecotones should be monitored by remote sensing techniques.

7.2.2 Climatically sensitive parameters

It is difficult to distinguish the responses of species, populations and communities to specific changes in climate from their responses to other stress factors. The monitoring system should therefore be organised in such a way that we can add new and better parameters later when the research community has made progress on climatically sensitive parameters. So far, we would like to emphasise the following methods.

Demographic studies of plant species. Demographic studies should be carried out on tree species and other ecologically important species (annuals?) in all the intensively monitored areas and probably in some extensive ones. Important parameters to monitor are:
- ability to survive and to produce seed (gives the reproduction rate λ)
- establishment

Ecotonal boundary monitoring (see chapter 7.1.3). We think this should be the flag method globally, regionally (Europe), nationally and locally within the field of climate change monitoring. The main idea is that most ecotones have sharp climatic gradients in which many species are at the limit of their distribution. It is therefore suggested that ecotones are very sensitive to climate change. A general design for the method is shown in **Figure 13** (see hypothesis p.). The best known ecotones in northern latitudes are the alpine and arctic timberlines. We suggest that the empiric treelines of Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and birch (*Betula pubescens*) are very sensitive to increases in temperature, i.e. they can easily move upwards or northwards.

Part of the ecotonal boundary method (**Figure 13**) should involve studying transects across the timberline (alpine or arctic) in specific monitoring areas. Demographic studies should also be carried out on treeline-forming and other important species in a zone embracing 100 vertical metres on each side of the timberline.

Other sensitive ecotones that are being monitored in Norway are the gradient across large river valleys and the snow bed-ridge ecotone. Flat river-valley bottoms will no doubt be sensitive and will change drastically if the hydrological scenarios proposed by NVE (the Norwegian Water Resources and Energy Administration) (Sælthun et al. 1990, Sælthun 1991) materialise.

The drought factor is critically important for the temperate deciduous forest-steppe biome ecotone (in southeastern Europe, central North America and Argentina). In subtropical and tropical regions, too, it limits the expansion of trees and shrubs across the tropical forest-savanna ecotone, the savanna-scrub steppe ecotone and the scrub steppe-desert ecotone, e.g. in Africa south of Sahara.

In flat landscapes, longer and wider transects need to be defined across the ecotonal boundaries.

7.2.3 Structure and organisation (see also chapter 7.1.6)

On a national scale, Norway has established many monitoring programmes that include biological parameters. The most relevant one for monitoring climate change is TOV (Programme for Monitoring Terrestrial Ecosystems) started by the Directorate for Nature Management in 1990. TOV includes 8 boreal forest and alpine areas and is aimed at monitoring effects of long-range pollutants, but can easily be extended to include sensitive parameters for climate change.

The AMAP programme (Arctic Monitoring and Assessment Programme), initiated in Oslo in November 1990, is a joint pan-Arctic research and monitoring programme so far largely focusing on pollutant monitoring but easily capable of being extended to include climatically sensitive biological parameters. AMAP also intends performing integrated baseline studies and research to fill gaps in our knowledge on arctic ecosystems. IASC (International Arctic Science Committee) will play a role in coordinating monitoring and research in the AMAP programme. The participating countries are the Arctic countries: Canada, USA, USSR, Norway, Sweden, Finland, Denmark/Greenland and Iceland. The permanent AMAP programme can be started in 1997.

Because of the wide range of biomes on a global scale and the long geographical distances involved, it may be rational to regionalise the administration of research and monitoring activities, as proposed at an IGBP meeting in Bellagio in November 1990 (the START initiative). That meeting established 14 representative, geographically coherent, regions (Eddy et al. 1991), each one being fairly homogeneous as regards biogeographical and climatic characteristics. Norway and Europe are included in the TNH (Temperate Northern Hemisphere) region, a vast area embracing most of the middle-latitude regions of the northern hemisphere, extending from the foothills of the Rocky Mountains in North America to an eastern limit at the forested regions of Eurasia. Its northern boundary is the Arctic Circle. START (System for Analysis, Research and Training), as proposed at the Bellagio meeting, may have a linking and coordinating function between the regional research and monitoring systems. START will very soon initiate an RRN (Regional Research Network) for each of the regions.

To attend to natural terrestrial ecosystems on a global scale, including the administration, total infrastructure and research/monitoring priorities, the hierarchy of ICSU (International Council of Scientific Unions) - IGBP (International Geosphere Biosphere Program) - GCTE (Global Change and Terrestrial Ecosystems) seems to constitute the best structure and organisation. However, there should be intimate contact with UNEP (United Nations Environmental Program) and IUCN (International Union for Conservation of Nature).

At a symposium in Trondheim in November 1990 on the Impact of Climatic Change, the CSSE (Committee for Cooperation and Security in Europe) was proposed as a possible body for coordinating and/or funding ecological climate change research and monitoring in boreal and arctic/alpine areas. It also emphasised the primary role of ICSU, IGBP and IUCN as coordinating agencies (Baadsvik & Schei 1991).

7.2.4 Recommendations

- establish a list of climatically sensitive biological parameters (arrange a workshop)
- establish national and regional networks for ecological monitoring (including climatically sensitive parameters), at extensive and intensive levels; discuss criteria for choice of sites (workshop?)
- harmonise with existing monitoring programmes (arrange a meeting between the bodies of the major regional programmes?)
- establish secretariat functions, regionalisation
- organise data bases for data from monitoring programmes
- obtain improved funding, allocation of resources (manpower, equipment, etc.) (arrange a workshop)

8 Concluding remarks

8.1 General

This report has, for the first time, outlined the areas of Norway most sensitive to changes in the climate (**Figure 14**). We have also made the first predictions of specific changes within plant communities in these areas. This has, to a large extent, been possible because of our increased understanding of the impacts that climate change will have on the hydrological systems of Norway. The predictions for the changes in the amount of snow falling and the length of time that snow will lie on the ground are especially important. These figures are of great significance when we attempt to predict the changes expected in the mountain plant communities of Norway (Chapter 4).

Climatic factors have been shown to ultimately limit the distribution of many species (e.g. Huntley et al. 1989) and predictions have been made (Chapter 5) outlining where the climate spaces of species and physiological groups of species are going to occur following the 2 x CO_2 scenario for climate change (Eliassen et al. 1989).

The time lag in the response of species within plant communities is such that it will be centuries before the vegetation catches up with the climate changes (Davis 1989, Huntley 1991). Some plant communities, however, will probably change considerably more rapidly and could be measurable in terms of decades. Examples of these rapidly changing communities include the disappearance of elm in *Ulmus glabra-Tilia cordata* forests due to disease (Chapter 4.4.2) or the invasion of pine and spruce into the dry, open birch forests of Finnmark (Chapter 4.4.4).

We have suggested that changes in existing communities will normally occur if those communities are disturbed in some way (Chapter 3.2 and Chapter 4). Different disturbances are likely to occur in the different sensitive areas of Norway (**Figure 14**). As disturbances are typically random events and do not occur across the whole of the boundary between two plant communities, we can expect the expansion of one plant community into another to occur as a series of "jumps" rather than as a steady "moving wave". The random nature of plant dispersal will add to this effect.

One of the more optimistic results of introducing the unpredictability of disturbance into plant community scenarios is that the number of rare species are predicted to become extinct is less than in more static correlative models (Chapter 6.2).
We must stress that our predictions are only "possible outcomes" resulting from the myriad of different factors affecting plant communities. Even by 2029 we are not going to be able to make certain predictions of which species will occupy any patch of land in Norway in 2030.

Too many of the factors which control plant communities are chance events, e.g. fire or flood, for certain predictions to be made. We can, however, improve our predictions to the extent where we can say which species will probably be occupying a particular patch of Norway. Predicted changes in the biodiversity of plant communities provide an example of where further research is required. Our predictions are not at all conclusive (Chapter 6.1). Biodiversity could increase or decrease by 2030.

To achieve these more satisfactory predictions we require better predictions of the changes in hydrology, which in turn depend on better climate scenarios. We also need considerably more information on the basic demography of the species within the plant communities of Norway. In this paper, we have outlined some methods (Chapter 7) which could provide this information.

Data from long-term monitoring of experimental plots and data from studies of plant physiology are vital if we are to make better predictions of the responses of vegetation to changes in the climate. This basic information is also vital if we are to predict vegetation responses to other unforeseen environmental changes or disasters.

8.2 Regional effects of climate change on the species, community and biome levels

The great local variation in most ecological factors within each of the ecoclimatic sensitivity regions outlined in **Figure 14**, we will produce a range of types of response in each of the regions. The greatest changes will perhaps not come from direct temperature effects, but from various physical disturbances brought about by extreme weather events. In the northern boreal and alpine region (Region I) the most sensitive plant species and communities are probably located on the mesic leeslopes and in damp depressions.

The seasonality of the hydrology and growing season in the upper part of the boreal biome and the alpine biome depends very much on the duration and depth of the snow cover. It is suggested that the mesophilous and hygrophilous species and plant communities within region I (**Figure 14**) will be the most sensitive and perhaps vulnerable ones. This sensitivity will be especially pronounced along the ridge-snow bed gradient, the *Vaccinium myrtillus* zone and the snow bed communities below. Another consequence of a reduction in snow cover is that the exposed ridge communities containing *Empetrum hermaphroditum*, *Loiseleuria procumbens*, etc., will probably expand, as those species are well adapted to harsh conditions such as wind chill and rapidly fluctuating temperatures.

The tall herb communities in the northern boreal zone may be threatened by the drier conditions in the growing season. In continental parts of southern Norway birch may in part be replaced by spruce, at least on mesic sites. The xeric and oligotrophic sites will probably be invaded by pine. However, the potential invasion of spruce and pine will be very slow. Clear-felling of trees in the northern boreal forests may enhance the negative effects of climate change.

Many types of physiological response exist in the lowland forest region (Region II in **Figure 14**). One of the most sensitive plant communities in region II may be the Ulmus Tilia forest, due to the probable invasion of Dutch elm disease (chapter 4.3.4) to much of southern and central Norway. This change and the possible invasion of pine and spruce into the dry, open birch forests of Finnmark and parts of inner southeastern Norway (chapter 4.4.4) are examples of rapidly changing communities and may be measurable in terms of decades.

Sælthun's (1991) hydrological scenario indicates increasing soil moisture deficits in the early part of the growing season. This may favour pine at the expense of spruce in southeastern Norway and Trøndelag.

Extreme events, like the hurricane in central Norway (1st January 1992) created large gaps in the boreal forests and make invasion by species that are better adapted to the new climate and hydrology much easier.

The predicted higher winter temperatures will in general hamper real boreal species like spruce (see the hypothesis in chapter 5.2), and favour the more frost-sensitive, oceanic species. However, most of the latter group will probably not "march" northeastwards in Scandinavia unless large gaps are created in the boreal forest.

The diverse fjord and coastal region (Region III in **Figure 14**) will probably show major changes on the steeper fjord slopes where extreme floods and other physical disturbances may increase erosion and landslides, creating large gaps. A floristic change on steep unstable slopes may take place in a few decades in western Norway. Many temperate grass and herbaceous species such as *Bromus benekeni*, *Brachypodium sylvaticum*, *Festuca altissima*, *Festuca gigantea*, *Carex sylvatica* and *Sanicula europaea*, may be favoured, especially if Dutch elm disease kills most elm stands.

The sensitivity of the coastal *Calluna* heaths to climate change is very uncertain. *Calluna vulgaris*, itself, may be less sensitive than some other heathland species. For example, the frost-sensitive *Hypericum pulchrum* and *Lonicera periclymenum*, will probably expand.

Mire and bog communities that are likely to be very sensitive to climate change in all the areas we have listed. Ombrotropic bogs in southeastern Norway which face drier conditions with increasing soil moisture deficits, will probably have floristic changes in a few decades.

Region IV in **Figure 14**, the river valley bottoms, is so far characterised as being as sensitive as region I. Floristic changes may take place in a few decades if the river systems no longer have a spring flood. We suggest that spruce may rapidly (a few decades) invade natural river plains from the neighbouring slopes and outcompete grey alder, if the runoff of most rivers should be like that indicated in **Figure 1**.

The most effective climate-induced processes giving the most rapid floristic and vegetational changes are hydrological processes. Other climate-induced processes (decomposition etc.) that change the nutritional status of plants are certainly important but much slower, having only long term effects on flora and vegetation.

8.3 Effects on biodiversity, rare or threatened plants

The effects of climate change and changes in hydrological conditions will be quantitative rather than qualitative during the first decades. What will happen can probably be compared with the quantitative floristic changes that take place quickly after clear-felling of a closed forest stand. In clear-fellings the balance between species is drastically changed, due to the abrupt changes in the microclimate and light conditions, and the rapid turn-over of organic matter. However, very few new species invade, and very few species become extinct.

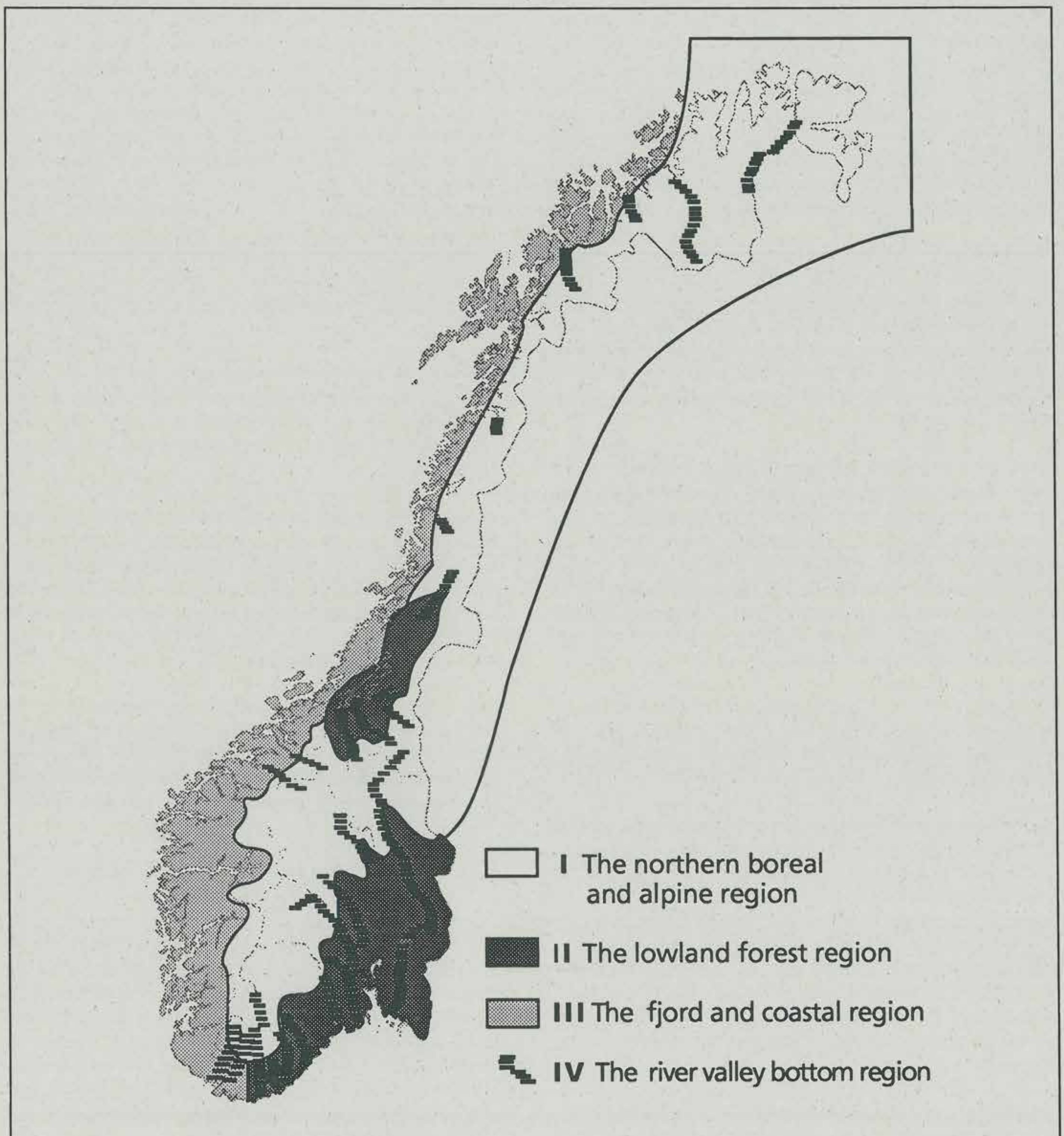

I The northern boreal and alpine region
II The lowland forest region
III The fjord and coastal region
IV The river valley bottom region

Figure 14
A sketch of ecoclimatic sensitivity regions of Norway.
I The northern boreal and alpine region
Main climate-induced disturbances
- *less snow cover (depth and duration)*
- *increased risk of late frosts*
- *increased mass movements*

Main ecological effects
- *threat to and potential die-back of alpine plant populations*
- *floristic change of mountain forests*

II The lowland forest region
Main climate-induced disturbances
- *increased drought stress*
- *increased frequency of forest fires*
- *increased number of attacks by pests (insects)*

Main ecological effects
- *decrease of spruce forests*
- *increase of pine forests and more open forests*
- *increase of xerophytes and xerophilous plant communities*
- *invasion of boreal forests by more thermophilous species, especially weedy species*

III The fjord and coastal region
Main climate-induced disturbances
- *the increased stress to boreal species caused by mild winters*
- *more landslides in steep terrain*

Main ecological effects
- *the decrease of boreal flora*
- *the increase of frost-sensitive species*

IV River-valley bottoms
Main climate-induced disturbances
- *increased erosion/sedimentation*
- *increased or decreased flooding*

Main ecological effects
- *the invasion of grey alder stands by Norway spruce*
- *more weeds*
- *eutrophication*

These four regions can be ranked in order of sensitivity
I = IV > II > III

A qualitative change in the Norwegian flora including immigration of new species and extinction of existing species, will probably be a very slow process, that will be very difficult to predict as species behave individualistically. Many natural migration barriers (expanses of sea) exist that could prevent or at least slow down for centuries the invasion of southern (thermophilous) and western (oceanic) species from the continent and the British Isles (see **Figure 6**). When they do become established in the southern part of Scandinavia, the thermophilous species from temperate Europe will face new barriers to western and central Norway, notably the fragmented anthropogenic landscape. The fjords and mountains of southern Norway will constitute further natural barriers separating them from the new climate niches in central or perhaps northern Norway. Extreme weather events can cause relatively sensitive species to become extinct in Norway and strengthen the foothold of more trivial species, such as *Deschampsia flexuosa*, *Deschampsia cespitosa*, *Epilobium angustifolium*, *Molinia caerulea*, *Filipendula ulmaria*, *Anthriscus sylvestris*, *Ranunculus acris* etc., many of which are indicative of increased nitrification. This will result in reduced biodiversity. It seems likely, therefore, that the northern part of the country and the alpine biome will be most vulnerable to such a reduced biodiversity. Mesophilous (*Vaccinium myrtillus*) to hygrophilous species (tall herbs, certain hepatics) will probably be more vulnerable than xerophilous ones (*Festuca ovina*).

12 species listed in **Table 2** may be threatened by climate change (see complete list chapter 6.1). Most of them grow in rare habitats, except for *Butomus umbellatus*, *Moehringia lateriflora*, *Melandrium angustifolium* and *Silene tatarica*. The poor migration capacity of many of the rare species, and the long distances between potential habitats make many of the rare species highly endangered. The most endangered group is probably middle and high alpine species (above 1400 m.a.s.l. in southern Norway) like *Poa stricta*, *Stellaria crassipes* and *Campanula uniflora*.

8.4 Critical levels and rates of change and tolerance limits of species and communities

The climate scenarios predicted, both the IPCC scenario indicating a 1.5-4.5°C increase in global temperature in 40 years and the specific Norwegian scenario, represent very quick changes in the ecological conditions of the Norwegian biota. It is difficult to say what the critical levels of temperature rise are going to be, as the most important factor is going to be **extreme events** like storms, floods, droughts and hard frosts. What will be the critical are the temperature rises themselves which will lead to an increase in these events. Experiments, both at species (laboratory experiments) and community (field experiments) level, will be required to determine the specific tolerance levels of species and the rates of temperature change. A rate of change of 0.5 °C per decade in the yearly mean is going to be significant if it leads to a high frequency (yearly) of hurricanes of the type that swept western and central Norway on January 1st 1992.

In order to assess whether changes in plant communities will develop linearly or in sudden "jumps", and the rate of those changes, the ecological research community need a lot of more information about ecosystem process, dynamics of ecosystems on species, population and community level. This lack of basic knowledge will probably limit the certainty of ecological impact scenarios and models the next decades. However, as the climate scenario includes both a higher frequency and intensity of weather and climate-induced extreme events (e.g. more and stronger storms), the most probable ecological response will be non-linear in Norwegian ecosystems. This non-linear response type will probably be most visible in forest areas, as storm-felling of trees, creating gaps, will lead to abrupt changes in the light climate and thereafter the next 1-3 years in nutritional conditions for the ground flora and fauna. A linear response type in the ecosystems will probably depend on a systematic change only in the mean values (temperature, precipitation).

9 Summary

Scenarios, population processes and gap theories
The ecological impact scenarios discussed in this report are based on a specific climate scenario made for Norway, indicating an increase of about 2 °C in summer temperature and 3-4 °C in winter temperature (the most probable scenario) through a doubling of atmospheric CO_2 equivalents. To a lesser extent we have used the IPCC scenario, which indicates an increase in the global mean temperature of 1.5-4.5 °C. Climate change also leads to changes in the run-off of rivers, hydrology and soil moisture deficits. For our impact scenarios we have stressed changes in the hydrological conditions and soil moisture deficits. Among the biological processes we have stressed the population dynamics of species, depending on birth, death, immigration and emigration of plants. It is suggested that the main changes will be initiated by the creation of relatively large gaps in closed plant communities by extreme events like storms, floods, droughts and episodes of hard frost.

Ecoclimatic sensitivity regions
The term ecoclimatic sensitivity is discussed at the species and plant community levels for each of the biomes, temperate, boreal, alpine and arctic. The sensitivity regions are outlined in **Figure 14** for the mainland (Svalbard not included). For each region, the main climate-induced disturbances and the main ecological effects of those disturbances are listed. Two regions are characterised as being particularly sensitive to climate change, although both have different climate-induced disturbances (**Figure 14**). They are the northern boreal (mountain forests) and alpine region (Region I) and the river valley bottom region (Region IV). In region I, the snow climate has a major influence on the occurrence of plant species and communities, in that they are adapted to short growing seasons (1-3 months). In the dormant period, the snow cover can also give protection from hard frost. The snow is also extremely important as it provides the main water supply for many plant communities for long periods during the summer. The snow cover scenario (see **Figure 2**) will change the depth and duration of snow cover drastically and therefore also the ecological conditions for mountain and mountain forest plants. The most vulnerable species and communities will probably be those of the mesophilous lee-slope (from the *Vaccinium myrtillus* zone downwards) and the snow-beds. The latter group of plant communities especially will face an uncertain future including a retreat downwards along the ridge-snow-bed gradient. As a result their total cover will shrink.

Intensive forestry management (clear-felling) in the northern boreal zone will be a form of disturbance that could make this region still more vulnerable to climate change.

Region IV, flat river valley bottoms, will probably experience a major change in hydrology reducing the vitality of grey alder (*Alnus incana*). In a few decades Norway spruce (*Picea abies*) may establish at the edges of natural river plains in southeast Norway and Trøndelag.

The arctic region (Svalbard) is dominated by the same physical disturbance regimes as the alpine environments on the mainland, except the added effects of permafrost must be included. It is suggested that Svalbard may experience greater ecosystem changes than the alpine region (Region I), due to changes in the active layer above the permafrost and the predicted higher temperature increase at higher latitudes.

Natural population processes may cause invasion of pine and maybe spruce into the open lichen-birch forest in northern Scandinavia. This may have a major influence on both the quality and quantity of grazing land for the reindeer.

The least sensitive region, the lowland forest region (Region II), including most of the temperate, hemiboreal, southern and middle boreal forests, will experience a higher climate-induced drought stress that will probably increase the frequency of forest fires and the number of attacks by pests (insects). One of the most sensitive plant communities in region II may be the *Ulmus-Tilia* forest (in a broad sense), where elm (*Ulmus glabra*) may be attacked by the Dutch elm disease.

However, we feel that the impacts on region II are much harder to predict than those of other regions because this region, currently contains certain species considered to be competitively dominant in addition to the strong anthropogenic influence. High human population density causes fragmentation of natural habitats in region II, making migration barriers for plants and animals. We think that the effect on region I and the arctic are more predictable as they represent more "physical environments" with less interspecific competition and less fragmentation of natural habitats.

Strong competition between spruce and pine, favouring the latter, maybe experienced in region II, the main cause being increased soil moisture deficits in the growing season. There will be a parallel expansion of xerophytes (*Festuca ovina*) and xerophilous plant communities.

For open alpine environments it is suggested that charges both in extremes and mean values of climate parameters will be of importance, whereas the forest biome will be more responsive to extreme weather events, become of the gap-forming potential of the latter.

Biodiversity, rare or threatened species

The first stage (the next decades) of ecosystem change in a warmer Norway may become detectable as quantitative rather than qualitative floristic changes, such as we can see during the first years after clear-felling of spruce stands. A lot of migration barriers (natural and anthropogenic) will prevent the invasion of the more thermophilous temperate species into the boreal coniferous landscape of Scandinavia during the coming centuries or maybe thousands of years.

It is suggested that there will be a considerable time-lag between the climate changing and the expected changes actually occurring in the hemiboreal and southern boreal spruces forests of Scandinavia. We think that the real change cannot take place before a great deal of the acid raw humus is decomposed and transformed into more mull-like soils. This should take centuries. However, extreme events with much storm-felling of trees will expose more neutral mineral soils and enhance the process of invasion of pioneer species of more southern origin into the boreal forests, and therefore increase biodiversity. The time lag for this response will probably be much greater for boreal forests in central and northern Norway. The latter forest regions may in fact experience a transient decrease in biodiversity.

The impact of climate change on biodiversity will to a great extent depend on the frequency and intensity of extreme weather events followed by various climate-induced disturbances (erosion, landslides etc.). More certain predictions about biodiversity will presuppose better climate and hydrological scenarios and much better knowledge about demographic processes of plants. Altogether 12 species on the lists of rare and threatened vascular plants in Norway may be threatened (directly or indirectly) by climate change. In **Table 2** these species are given the value 3 in column 3. In the same Table nine other species are identified by threat category 2 (substantial change) in column 3. Most of the threatened species are northern or alpine ones. Species having their optimum in the middle and high alpine vegetation zone (above 1400 m a.s.l. in southern Norway) are especially threatened, e.g. *Poa stricta*, *Campanula uniflora* and *Stellaria crassipes*. Other rare species are not threatened by climate change or may even become more common in a warmer climate regime, e.g. *Rorippa islandica*, *Ribes nigrum* and Genista tinctoria. Some rare southern (thermophilous) and thermic oceanic species will probably be favoured by a warmer climate, especially by the warmer winters, e.g. *Ilex aquifolium*, *Erica cinerea* and *Asplenium marinum*.

Research and monitoring needs

We have pointed out three areas where major gaps in knowledge exist:

- migration rates of species
- establishment of species
- ecosystem sensitivity

As regards the approaches, the research effort should be concentrated on:

- observation/monitoring (descriptive part)
- population dynamics
- experimentation (causal part)
- modelling

We have proposed that much of the research and monitoring effort should be allocated to typical ecotonal boundaries, based on the hypothesis that "ecotones are areas that are particularly sensitive to climate change as they represent marginal localities or areas for many species due to a steep climatic or other type of abiotic gradient". Relevant ecotones for Norwegian or joint boreal research/monitoring effort are the alpine timberline and forest tundra ecotone
(arctic timberline). The observation/monitoring part of the research should include autecological studies in areas with high ß diversity. Phenological studies and digitising/gridding of existing distributional data sets should be carried out.

To reveal causal relationships in ecosystems, it will be important to carry out various experiments, both under controlled laboratory conditions and in the field on population and plant community level. The most relevant experimental approaches are transplantation/genetic experiments, greenhouse techniques and soil-warming techniques.

The ultimate objective for ecologists is the construction of fairly reliable impact models. This will involve intimate team work between climatologists, hydrologists, statisticians, ecologists (with expertise in various fields), computing experts and modellers. In the short term, a relatively strong research effort should be put into developing correlative models (e.g. the relationship between distribution and climatic parameters) because most dynamic models will depend on an improved knowledge of ecosystem processes.

As regards the administration of impact research and monitoring related to climate change, we propose strong international links. We think that the axis ICSU - IGBP - GCTE will be very important for impact analyses on terrestrial ecosystems. However, there is no doubt a need for some sort of regionalisation of the climate change research effort, for example as proposed in the START initiative and the proposal to establish a "subcore office" of GCTE for boreal and arctic regions at the Norwegian Institute for Nature Research in Trondheim.

In all, 7 European conservation research institutes, including the British ITE and the Norwegian NINA, have started a cooperation, in which "impact studies on climate change" is one of the four topics given priority; this is the CONNECT system.

The following flag activities for research and monitoring are recommended:

- establishment of short and long term regional research programmes on ecological impact studies, including aspects of both observation, experimentation and modelling
- establishment of integrated national, regional (e.g. Europe or boreal to arctic areas) and global networks on research and monitoring sites (e.g. the GCTE network), covering both major climate gradients and transects across ecotones
- digitisation and gridding of existing distributional data sets (e.g. Atlas Florae Europaeae)
- Establishment of national, regional and global data bases for distributional data associated with climatic parameters

For Norway we recommend a network of 2 or 3 geographical areas for intensive research and monitoring. Each area should be able to household international research teams for relatively long periods. It should therefore have a good infrastructure, that is, good access, lodging possibilities and laboratory facilities. In addition a good area protection is necessary and the site should cover a major natural ecotone. Automatic gauging of both climatic and hydrological parameters will also be important. We recommend the "**ecotonal boundary method**" for both research and monitoring. The main activity should be demographic studies of plant species.

Main conclusions

We have based air preliminary outline of four ecoclimatically sensitive regions of Norway on the various climate spaces and other ecological demands of plant species, combined with the Norwegian climate scenario and hydrological scenario. It is suggested that the alpine and northern boreal region (Region I) and the river valley bottom region (Region IV) are the most sensitive ones to climate change in mainland Norway. The arctic biome (in this case, Svalbard) may be still more sensitive. We suggest that major changes in the most sensitive plant communities may be initiated through various climate-induced disturbances of which the formation of quite large gaps in climax forest vegetation will be the most important one for the forest region, as gaps make the areas much more capable of being invaded. Direct gap-forming agencies are wind-felling, erosion, landslides, pests (e.g. insect attacks on tree species).

Major changes may take place in mesic and hygric communities, including lee-slope and snow bed communities in the alpine biome, due to changes in snow cover and hydrology. For the same reason, the forest biome, i.e. the northern boreal birch forest biome, may change with the xeric sites possibly being invaded by pine and the mesic to hygric ones by spruce. The change may include the invasion of pine into the drier mountain birch forests and spruce into mesic (*Vaccinium myrtillus* and low herb types) and damper types (tall herb types) of mountain birch forests. Birch may in the course of a few decades establish in the current lee-slope vegetation in the low alpine zone, and in this way move the timberline upwards in areas having deep loose deposits.

There will be a general increase in xerophilous species and communities in southeastern Norway. Dutch elm disease may reduce the elm (Ulmus glabra) stands considerably in the temperate and hemiboreal zone. Altogether 12 currently rare or threatened plant species may come under threat of disappearance owing to climate change. 8 other currently rare or threatened plant species may experience substantial reductions in their populations.

It is suggested that the Norwegian climate scenarios will lead to a non-linear response type in ecosystems, the initiating factor being change in extreme events towards higher frequency and intensity. This non-linear development is most probable in our forest areas where extreme weather events may create larger gaps in the tree layer, starting rapid secondary successions.

The certainty of ecological impact scenarios the next decades will to a high extent be limited by the lack of basic knowledge about important ecosystem processes, for example demographic processes. This basic knowledge is indispensable for the production of better impact models, and is as important for the assessment of critical rates/levels of ecosystem change and tolerance limits of single species.

10 Sammendrag

Scenarier, populasjonsprosesser og 'gap'-teorier

De økologiske virkningsscenariene som er diskutert i denne rapporten er basert på et klimascenario laget for Norge. Dette norske klimascenariet indikerer en økning på ca 2°C i sommertemperaturen (middel for juni, juli og august) og ca 3-4°C i vintertemperaturen (desember, januar og februar), ved en fordobling av atmosfærisk CO_2-ekvivalenter. Vi har i mindre grad brukt IPCC-scenariet som indikerer en økning i global middeltemperatur på 1,5-4,5°C. Klimaendringer fører også til endringer i avrenning for elver, hydrologi og 'soil moisture deficits'. I våre virknings-scenarier har vi like mye lagt vekt på klima-induserte endringer i hydrologiske forhold og 'soil moisture deficits', som endringer temperatur- og nedbørsforhold. Blant de biologiske prosessene har vi lagt vekt på populasjons-dynamikk hos arter, som er avhengig av fødselsrate, dødsrate, immigrasjon og emigrasjon av planter. Vi ønsker at hovedendringene vil bli initiert av dannelsen av relativt store 'gaps' (åpninger) i lukkede plantesamfunn gjennom ekstreme værepisoder som stormer, flommer, tørkeepisoder og harde frostepisoder.

Økoklimatiske følsomhetsregioner

Begrepet økoklimatisk følsomhet er diskutert på arts- og plantesamfunnsnivå for hvert av biomene temperert, boreal, alpin og arktisk. Følsomhetsregionene er avgrenset i **figur 14** for fastlands - Norge (Svalbard ikke inkludert). For hver region er den viktigste klima-induserte forstyrrelsestypen (disturbance regime) angitt i tillegg til antatte økologiske virkninger av disse forstyrrelsene. To regioner er karakterisert som særlig følsomme i forhold til klimaendringer, men forårsaket av forskjellige klima-induserte forstyrrelsr (**figur 14**). Disse er nordboreal region (fjellskogene) sammen med alpin region (region I) og "elvesletteregionen" (region IV). I region I har snøklimaet en hovedvirkning på forekomst og utbredelse av plantearter og -samfunn, etter som disse er tilpasset en kort vekstsesong (1-3 måneder). I hvileperioden gir snødekket beskyttelse fra ekstrem frost. Snøen er også ekstremt viktig for vannforsyningen for mange plantesamfunn i lange perioder om sommeren. Snødekkescenariet (**figur 2**) vil forandre dybden og varigheten av snødekket drastisk og derfor også de økologiske forholdene for fjell- og fjellskogplanter. Den mest følsomme fysiologiske responstypen vil sannsynligvis være mesofile lesidearter og -samfunn (fra blåbærsonen og nedover mot snøleiet) og snøleiearter og -samfunn. Spesielt sistnevnte gruppe av plantesamfunn vil gå en usikker fremtid i møte, med reduksjon av arealer og forandring av artssammensetning.

Intensivt skogbruk (snauhogst etc.) i nordboreal region vil være en form for antropogen forstyrrelse som kan gjøre denne regionen enda mer sårbar for klimaendringer.

Region IV, elvesletteregionen, vil sannsynlig få en hovedendring i hydrologi som vil redusere vitaliteten til gråor (*Alnus incana*). Etter noen få tiår kan gran (*Picea abies*) etablere seg på forhøyninger på naturlige elvesletter i Sørøst- og Midt-Norge.

Arktisk region (her Svalbard) er i stor grad dominert av de samme fysiske forstyrrelses-regimer som alpine miljøer på fastlandet, med inntak av permafrost. Det antas at Svalbard kan få større økosystemendringer enn alpin region (region I), både på grunn av forandringer i det aktive laget og den forutsagte høyere temperaturendringen på høyere breddegrader.

Naturlige populasjonsprosesser kan forårsake invasjon av furu og kanskje gran inn i den tørre og åpne lavbjørkeskogen i nord-Skandinavia. Dette kan få store virkninger, både kvalitativt og kvantitativt for reinbeitet.

Vi antar at skogregionen (region II), det vil si temperert, hemiboreal, sør- og mellomboreale skoger, vil ha en middels til høy økoklimatisk følsomhet. Region II vil sannsynligvis få et økt klimaindusert tørkestress, særlig i Sørøst-Norge og øst for Trondheimsfjorden. I disse områdene kan man få økt hyppighet av skogbranner og hyppighet av skogsinsektangrep. Et av de mest følsomme plantesamfunnene i region II kan være almlindeskogene (vidt oppfattet), hvor alm (*Ulmus glabra*) kan risikere omfattende angrep av almesyken (Dutch elm disease).

Vi føler imidlertid at virkningene på region II er mye verre å forutsi enn hva som er tilfelle for de andre regionene, etter som denne regionen til en stor grad er et "biotisk" miljø med sterk naturlig interspesifikk konkurranse i tillegg til sterk antropogen påvirkning.

Stor befolkningstetthet har forårsaket **fragmentering** av naturlige habitater i region II. Dette har ført til vandringsbarrierer for planter og dyr. Vi mener at virkningen på region 2 og arktis er mer forutsigbar ettersom de representerer mer fysiske miljøer med atskillig mindre interspesifikk konkurranse og mindre fragmentering av naturlige habitater.

I den harde konkurransen som vil finne sted mellom furu og gran i region II, på grunn av økt 'soil moisture deficits' i vekstsesongen, vil vi sannsynligvis få en økning av førstnevnte. Tørkeelskende og tørketålende planter (f.eks. sauesvingel (*Festuca ovina*)) og plantesamfunn vil ekspandere i region II, mens de meso- og hygrofile kan gå tilbake, f.eks. blåbær- og bregneskoger.

Biodiversitet, sjeldne og truete arter
Det første stadiet (noen tiår) av økosystemforandringer i et varmere Norge kan kanskje bli dokumentert som kvantitative floraendringer, for region II i prinsippet slik som vi ser det etter snauhogst av granbestander. Flere typer vandringsbarrierer (naturlige og antropogene) vil forhindre en invasjon av mer varmekjære arter fra tempererte Mellom-Europa inn i det boreale barskogslandskapet i Skandinavia de neste århundrene eller kanskje årtusener.

Det antas at de hemiboreale, sør- og mellomboreale granskogene i Skandinavia vil ha en svært stor tidsforskyving (time lag) før vesentlige floraendringer vil finne sted, inkludert kolonisering av mer tempererte arter. Vi mener at store endringer ikke kan finne sted før en stor del av den sure råhumusen er nedbrutt og forandret til et mer brunjordaktig jordsmonn. Dette kan ta århundrer. Imidlertid, ekstreme værepisoder med mye stormfelling av trær vil eksponere mer nøytral mineraljord og øke prosessen med invasjon av pionerarter av mer sørlig opprinnelse inn i de boreale skogene, og på denne måten øke biodiversiteten, i det minste for en periode. Tidsforskyvingen for denne responsen vil sannsynligvis være mye større for boreale skoger i Midt- og Nord-Norge. Det siste området kan faktisk få en gradvis senkning i biodiversiteten.

Virkningen av klimaendringer på biodiversiteten vil i stor grad avhenge av hyppighet og styrke (intensitet) på ekstreme værepisoder som ofte er fulgt av klima-induserte forstyrrelser som erosjon, ras osv. Sikrere forutsigelser om virkninger på biodiversiteten vil forutsette bedre klima- og hydrologiske scenarier og mye bedre kunnskap om demografiske prosesser hos planter. I alt 12 arter på listen over allerede sjeldne og truete karplanter i Norge, kan få sin eksistens truet (direkte eller indirekte) av klimaendringer. Disse artene er identifisert med truethetskategori 3 (truet av utrydding) i kolonne 3 i **tabell 2**. I samme tabellen er 8 andre arter identifisert med truethetskategori 2. Denne gruppen kan regne med betydelige bestandsreduksjoner. De fleste truete artene er nordlige eller alpine, etter som fullstendige lister ikke foreligger for arealer under skoggrensa. Arter som har sine optima i mellom- og høgalpin vegetasjonssone (over 1400 m o.h. i Sør-Norge) er spesielt truet, f.eks. Knutshørapp (*Poa stricta*), høgfjellsklokke (*Campanula uniflora*) og snøstjerneblom (*Stellaria crassipes*). Andre sjeldne arter, kanskje særlig de varmekjære, er ikke truet av klimaendringer, og de kan faktisk bli mer vanlig i et varmere klima, f.eks. brunnkarse (*Rorippa islandica*), solbær (*Ribes nigrum*) og fargegnist (*Genista tinctoria*). Noen varmekjære og termisk oseaniske arter vil sannsynligvis bli begunstiget av et varmere klima, særlig av de varmere vintrene, f.eks. kristtorn (*Ilex aquifolium*), purpurlyng (*Erica cinerea*) og havburkne (*Asplenium marinum*), som alle har sin europeiske nordgrense i Sør-Norge.

Forsknings- og overvåkingsbehov
Vi har utpekt tre fagområder hvor vi har vesentlige kunnskapsmangler:
- vandringshastighet hos arter
- etablering av arter
- følsomhet hos økosystemer

Med hensyn til metodisk tilnærming (approach), bør forskningsinnsatsen settes inn på følgende områder:
- observasjon/monitoring (deskriptiv del)
- populasjonsdynamikk
- eksperimenter (kausal del)
- modellering

Vi har foreslått at stor innsats bør settes inn på forskning og monitoring på økotoner, basert på en hypotese om at "økotoner er områder som er spesielt følsomme for klimaendringer etter som de representerer utkantlokaliteter eller -områder for mange arter på grunn av bratte klimagradienter eller andre typer av abiotiske gradienter". Relevante økotoner for norske eller felles boreal (USA, Canada, SUS, UK og Skandinavia) forskning- og monitoring-innsats er alpin skoggrense og skogtundra-økotonen (polar skoggrense), etter som forandringer i det termiske klimaregimet sannsynligvis vil forårsake vesentlige endringer i disse økotonene. Observasjons- og monitoringdelen av forskningen bør inkludere autøkologiske studier i områder med høy ß-diversitet. Fenologiske studier og digitalisering/"gridding" av eksisterende utbredelsesdata for arter bør også gjennomføres.

For å påvise årsakssammenhenger i økosystemer, er det viktig å gjennomføre eksperimenter, både under kontrollerte laboratorieforhold (for enkeltarter) og i felt på populasjons- og plantesamfunns-nivå. De mest relevante eksperimentelle metodene er transplantasjon/genetiske eksperiment, drivhusteknikker og jordvarmingsteknikker.

Innenfor den klima-relaterte økologien er det et hovedmål å lage så pålitelige virkningsmodeller som mulig. Dette vil kreve et intimt samarbeid mellom klimatologer, hydrologer, statistikere, økologer (ved variert ekspertise), dataeksperter og modellerere. På kort sikt bør det settes inn relativt stor forskningsinnsats på utvikling av gode korrelative modeller (f.eks. på relasjonen utbredelse-klimaparametre), fordi de fleste dynamiske modeller vil avhenge av atskillig større kunnskap om prosesser i økosystemene, f.eks. demografiske prosesser.

Med hensyn til organiseringen og administrasjonen av økologiske virkningsforskning og tilknyttet monitoring i forhold til klimaendringer, foreslår vi sterk internasjonal tilknytning. Vi mener at aksen ICSU-IGBP-GCTE bør være viktigst for globale og regionale virkningsundersøkelser og utvikling av globale virkningsmodeller for terrestriske økosystemer. Imidlertid, det er ingen tvil om at det er behov for en regionalisering (f.eks. Europa) av forskningssamarbeidet. Eksempler på slik regionalisering har man i START-initiativet (se kapitel 7) og forslaget til "Subcore office" av GCTE for boreale og arktiske områder som er foreslått lagt til Norsk institutt for naturforskning i Trondheim.

I alt 7 europeiske forskningsinstitutt innenfor anvendt økologi, inkludert det britiske ITE (Institute and Terrestrial Ecology) og det norske NINA, har startet et forskningssamarbeid, hvor "virkningsstudier av klimaendringer" er et av de fire tema som er gitt prioritet. Denne samarbeidsstrukturen heter CONNECT.

Følgende hovedaktiviteter for forskning og monitoring i forhold til klimaendringer er anbefalt for de neste 1-5 årene:

- Etablering av langsiktige regionale forskningsprogrammer på økologiske virkningsundersøkelser, med aspekter av observasjon/monitoring (deskriptiv) eksperimenter (kausal del) og modellering.
- Etablering av langsiktige nasjonale, regionale og globale nettverk av forsknings- og monitoring-områder, med utbygging/samarbeid med eksisterende nettverk (f.eks. GCTE-nettverket). Nettverket bør dekke de viktigste klimagradientene ved transekter over økotoner.
- Digitalisering og "gridding" av eksisterende utbredelsesdata (f.eks. Atlas Florae Europaeae).
- Etablering av nasjonale, regionale og globale databaser for utbredelsesdata assosiert med klimaparametre.

For Norge anbefaler vi et nettverk av minst 2, helst 3 geografiske områder for intensiv forsknings- og monitoring-innsats i forhold til klimaendringer. Hvert område skal være i stand til å ha internasjonale forskningsteam i lengre perioder. Området må derfor ha god infrastruktur, det vil her si atkomst, overnattings- og laboratoriefasiliteter. Et sterkt arealvern blir nødvendig og området bør dekke en viktig naturlig økoton, helst alpin skoggrense. Det blir også viktig raskt å etablere automatiske målestasjoner for både klima- og hydrologiske parametre. Vi anbefaler "økotonmetoden" (se kap. 7 og figur 13) som overordnet både for forskning og overvåking i intensivområdene. Hovedaktiviteten bør bli demografiske studier av plantearter.

Hovedkonklusjoner

Basert på planteartenes forskjellige klimatiske nisjer (climate space) og andre økologiske krav, kombinert med det norske klimascenariet og hydrologiske scenariet, har vi gitt et foreløpig utkast til fire økoklimatiske følsomhetsregioner for Norge. Det antas at snaufjellet sammen med nordboreal region (= region I) og "elvesletteregionen" (region IV) er de mest følsomme i forhold til klimaendringer i fastlands-Norge. Det arktiske biomet (Svalbard) er kanskje enda mer følsomt (ikke angitt på kartet). Vi antar at vesentlige endringer i de mest følsomme plantesamfunnene kan bli initiert av forskjellige klimainduserte forstyrrelser i økosystemene. Dannelsen av store åpninger (gaps) i klimaksskog vil utgjøre den viktigste forstyrrelsen i skogområdene. Slike åpninger vil legge forholdene til rette for rask invasjon av nye plantearter (pionerer) og på denne måten endre skogsamfunnenes artssammensetning. Eksempler på direkte "gap"-dannende hendelser er vindfelling av trær, erosjon, ras og angrep av skadeinsekter på trær.

Vesentlige økologiske virkninger kan man få i middels-fuktige og fuktige til våte plantesamfunn generelt. I fjellet (region I) vil dette omfatte lesidevegetasjon (blåbærsonen) og snøleiesamfunn, forårsaket av endringer i snødekket (dybde og varighet) og dermed hydrologien i vekstsesongen. Av samme grunn kan de nordboreale skogene (vesentlig fjellbjørkeskog) forandre seg (region I). Forandringen kan innebære invasjon av furu inn i de tørrere fjellbjørkeskogene og av gran inn i de middels fuktige (blåbær-typer, lågurttyper) og fuktige (høgstaudetyper) fjellbjørkeskogene. Fjellbjørka kan i løpet av få tiår etablere seg i dagens lesidevegetasjon i lågalpin fjellregion og slik flytte skoggrensa betydelig oppover i områder med mye løsmasser.

Vesentlig på grunn av de forutsagte endringene i hydrologien i Sørøst-Norge, vil vi her få en generell økning av xerofile arter og plantesamfunn. Almesyken (Dutch elm disease) kan komme til å redusere betraktelig almebestandene i temperert og hemiboreal sone. I alt 12 for tiden sjeldne og truete plantearter i Norge kan trues av utrydding på grunn av klimaendringer, 8 andre for tiden sjeldne og truete plantearter kan få betydelige reduksjoner i sine bestander.

Det antas at de mulige økosystem-endringene vil komme som en serie hopp (= non-linear development), initiert av ekstreme værepisoder. Slik ikke-lineært utviklingsforløp i økosystemene er mest sannsynlig i våre skogområder, hvor ekstreme værepisoder kan danne store åpninger i tresjiktet, som i sin tur vil sette i gang raske suksesjoner i skogbunnen. Sikkerheten i de økologiske virkningsscenariene de neste tiårene vil i stor grad begrenses av mangel på basiskunnskaper om viktige økosystem-prosesser, bl.a. om demografiske prosesser. Slike kunnskaper er uunnværlige for å lage sikrere virkningsmodeller. Slike basiskunnskaper vil være like viktige for fastsettelse av hastighet og retning av økosystemendringer.

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Appendix

List of plant names

Latin	Norwegian	English
Trees, shrubs		
Alnus incana	gråor	grey alder
Betula pubescens	bjørk	birch
B. nana	dvergbjørk	dwarf birch
Corylus avellana	hassel	hazel
Fagur sylvatica	bøk	beech
Fraxinus excelsior	ask	ash
Ilex aquifolium	kristtorn	holly
Picea abies	gran	Norway spruce
Pinus sylvestris	furu	Scots pine
Populus tremula	osp	aspen
Prunus padus	hegg	bird-cherry
Quercus spp.	eik	oak
Salix spp.	vier	willow
Tilia cordata	lind	small-leaved lime
Ulmus glabra	alm	wych elm
U. procera	engelsk alm	English elm
Dwarf shrubs		
Arctostaphylos alpinus	rypebær	black bearberry
A. uva-ursi	mjølbær	bearberry
Calluna vulgaris	røsslyng	heather, ling
Cassiope hypnoides	moselyng	
C. tetragona	kantlyng	
Empetrum hermaphroditum	fjellkrekling	crowberry
Erica cinerea	purpurlyng	bell-heather
Loiseleuria procumbens	greplyng	'Loiseleuria', trailing azalea
Lonicera periclymenum	vivendel	honey-suckle
Phyllodoce caerulea	blålyng	
Salix herbacea	fjellmo, musøre	least willow
S. polaris	polarvier	
Vaccinium myrtillus	blåbær	bilberry
Grasses, sedges		
Alopecurus arundinaceus	strandreverumpe	
Arctagrostis latifolia	russegras	
Arctophila fulva	hengegras	
Brachypoodium sylvaticum	lundgrønaks	slender false-brome
Bromus benekenii	skogfaks	hairy brome
B. mollis	lodnefaks	lop-grass
B. sterilis	sandfaks	barren brome

Latin	Norwegian	English
(Grasses, sedges cont.)		
Calamagrostis chalybaea	Nordlandsrørkvein	
Carex arctogena	reinstarr	
C. bicolor	kvitstarr	
C. bigelowii	stivstarr	
C. disperma	veikstarr	
C. ericetorum	bakkestarr	
C. lapponica	lappstarr	
C. scirpoidea	Grønlandsstarr	
C. stylosa	griffelstarr	
C. sylvatica	skogstarr	wood sedge
Deschampsia cespitosa	sølvbunke	tufted hairgrass
D. flexuosa	smyle	wavy hairgrass
Eriophorum gracile	småull	
Festuca altissima	skogsvingel	
F. gigantea	kjempesvingel	tall brome
F. ovina	sauesvingel	sheep's fescue
Holcus mollis	krattlodnegras	creeping soft-grass
Luzula arctica	snøfrytle	'arctic' woodrush
L. confusa	vardefrytle	
Molinia caerulea	blåtopp	purple moor-grass
Nardus stricta	finnskjegg	mat-grass
Phippsia algida	snøgras	
P. concinna	sprikjesnøgras	
Poa pratensis	engrapp	meadow-grass
P. stricta	Knutshø-rapp	Knutshø Poa
Roegneria fibrosa	russekveke	
Scirpus cespitosus	bjønnskjegg	deer-grass
S. pumilus	krypsivaks	
Trisetum subalpestre	kveinhavre	
Herbs		
Aconitum septentrionale	tyrihjelm	
Alchemilla alpina	fjellmarikåpe	alpine lady's mantle
Androsace septentrionalis	smånøkkel	
Anthriscus sylvestris	hundekjeks	cow parsley, keck
Arenaria humifusa	dvergarve	
A. pseudofrigida	kalkarve	
Braya linearis	rosekarse	
B. purpurascens	purpurkarse	
Butomus umbellatus	brudelys	flowering rush
Campanula uniflora	høgfjellsklokke	
Capsella bursa-pastoris	gjetertaske	shepherd's purse
Cerastium diffusum	kystarve	
Crepis multicaulis	Altaihaukeskjegg	

Latin	Norwegian	English
(Herbs cont.)		
Cypripedium calceolus	marisko	lady's slipper
Draba cacuminum	tinderublom	
D. cinerea	gårublom	
Dryas octopetala	reinrose	mountain avens
Epilobium angustifolium	geitrams	fireweed
Filipendula ulmaria	mjødurt	meadow-sweet
Galium pumilum ssp. normanii	bakkemaure	slender bedstraw
Genista tinctoria	fargeginst	dyer's greenweed
Geranium molle	lodnestorkenebb	dove's-foot cranesbill
Hippuris tetraphylla	krossreverumpe	
Hypericum pulchrum	fagerperikum	slender St. John's wort
Isatis tinctoria		vaid wood
Matricaria inodora	balderbrå	scentless May-weed
Melandrium angustifolium	småjonsokblom	
Mercurialis perennis	skogbingel	dog's mercury
Mimulus guttatus	gjøglerblom	monkey-flower
Moehringia lateriflora	russearve	
Narthecium ossifragum	rome	bog asphodel
Nigritella nigra	svartkurle	
Oxytropis deflexa ssp. norvegica	masimjelt	
Papaver dahlianum	Svalbard-valmue	Svalbard poppy
P. laestadianum	Læstadius-valmue	Læstadius poppy
P. lapponicum	Talvik-valmue	Talvik poppy
P. radicatum s.l.	fjellvalmue	mountain poppy
Polemonium boreale	polarflokk	
Potamogeton rutilus	stivtjønnaks	Shetland pondweed
Ranunculus acris	engsoleie	meadow buttercup
R. lapponicus	lappsoleie	
Ribes nigrum	solbær	black currant
Rorippa islandica	brønnkarse	marsh yellow-cress
Rumex acetosa	storsyre	sorrel
R. acetosella	småsyre	sheep's sorrel
Sanicula europaea	sanikel	sanicle
Saxifraga aizoides	gulsildre	yellow mountain saxifrage
S. cespitosa	tuesildre	tufted saxifrage
S. hirculus	myrsildre	yellow marsh saxifrage
S. opdalensis	Oppdalssildre	Oppdal saxifrage
S. oppositifolia	raudsildre	purple saxifrage
S. paniculata	bergjunker	
Senecio integrifolius	Finnmarkssvineblom	field fleawort
Silene tatarica	tatarsmelle	
Sorbus neglecta	Nordlandsasal	
Stellaria crassipes	snøstjerneblom	
Taraxacum dovrense	Dovreløvetann	Dovre dandelion
Thalictrum rariflorum	Finnmarksfrøstjerne	

Latin	Norwegian	English
(Herbs cont.)		
Viola mirabilis	krattfiol	
Zannichellia palustris	liten vasskrans	horned pondweed
Ferns		
Asplenium marinum	havburkne	sea spleen-wort
Blechnum spicant	bjønnkam	hardfern
Thelypteris limbosperma	smørtelg	mountain fern
Cryptogams		
Polytrichum sexangulare	snøbjørnemose	
Anthelia juratzkana	krypsnømose	
Cetraria delisei	snøskjerpe	
Phacidium infestans	snøskytte	

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