The response to global warming of plants restricted to north-western Britain

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If projected changes in climate occur during the next century, plant species which at present are growing at their southernmost limit in northwest Britain, are in danger of local extinction. To investigate this possibility, forty-one plant species were selected which are at risk. Their European distribution was established from published maps and captured on computer using a 50 km grid; the same grid was used to record European bioclimate data for three variables. Using this information, Response Surfaces have been derived; these model the relationship between species distribution and present climate. The results show that distribution of all the species is determined by macroclimate and illustrate how climate has constraints upon each species. Simulated future distributions have been obtained using 2 x CO_2 climatic scenarios derived from two alternative GCM's. These distributions show all of the species are likely to experience major changes in their "potential" range if climate changes occur. Many species would suffer substantial reductions in their numbers and range, and are threatened with extinction from the British Isles. Few plants, if any, will be able to maintain their range in equilibrium with the changing climate. To monitor what happens, five species were selected and sites for each identified in northwest England at which growth habits etc. were recorded. These sites can be revisited in future to assess the effects of "global warming". It is expected that the impact of changes in climate will vary depending upon the species and its habitat. The simulations of present and potential ranges take no account of other factors such as edaphic controls, photoperiodism, or the direct affect of CO_2, all of which will determine future distributions of the species studied.

THE RESPONSE TO GLOBAL WARMING OF PLANTS RESTRICTED TO NORTH-WESTERN BRITAIN.

A thesis submitted by

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Except for the text references to publications, the content of this thesis is entirely my own work. It has not previously been submitted for any degree or diploma.

Alison P. McDonald

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CHAPTER 1

Introduction

The aim of this investigation is to examine the possible effects of global warming on plants growing at their southern limit in northwest Britain. It is accepted that these plants are at risk as they are at the extremity of their natural distribution, and there are various reasons for their survival.

In the past there has been climate change, but never at the present magnitude, which is accepted to be due to human activity. Since the Industrial Revolution in the western world, there has been an exponential increase in population. With this there has occurred a complementary increase in the burning of fossil fuels which has lead to an increase in greenhouse gases with the resulting global warming.

Forty one plant species, Pteridophytes and Angiosperms have been selected after examining their morphology and physiology, as being at risk, having their southern limit in northwest Britain. All occur on mainland Europe with their main areas of distribution in the north. Maps showing the European distributions have been compiled. Five of the species, which are considered to be particularly at risk have had sites identified for their long term monitoring. These sites are all in the north west of England, and where possible varying in their micro environment.

Using computer software, distribution maps for all the selected species have been fitted with meteorological data for three bioclimate variables and response surfaces have been produced. A visual picture of climatic factors which limit the range of growth of these plants is thus obtained. These response surfaces are used to simulate the potential present distribution in Europe and this compared with the "actual" distribution.

To examine the effect of Global Warming scenarios have been obtained from two general circulation model simulations, these represent a high sensitive

United Kingdom Meterological Office 2 x CO_2 scenario (UKMO) (Mitchell 1983) and a lower sensitive Oregon State University 2 x CO_2 scenario (OSU) (Schlesinger 1989). The three bioclimate variables for each scenario are used to simulate the potential future distribution in Europe. These simulated distributions illustrate the magnitude of the possible changes in range of the individual species. With this information it is possible to make some estimation of the vulnerability of a particular species.

CHAPTER 2

The Climate

2.1 The Past Climate of the British Isles

Evidence of the Late-glacial and Post-glacial changes in the vegetation of the British Isles has accumulated in recent years. From the palynological analysis of peats and lake sediments there is emerging information as to how the vegetation of many parts of the British Isles has changed during the last 10,000 years. This evidence shows the dynamic nature of both the climate and the vegetation.

At the end of the Pliocene Age the British Isles was already a projection from the continent of Europe, and the changes which occurred during the late Pleistocene period influenced their flora. The Pleistocene Ice Age consisted of periods of glaciation interspersed by "warm" phases. The periods of warmth comprise interstadials, of shorter duration, and interglacial periods, long enough for temperate forests to develop in Britain (Watts, 1988).

The general improvement of the climate which lead to the most recent recession of the ice sheets and their disappearance from the British Isles took between between about 18,000 to 7,500 years ago (Roberts, 1989). During this time, insolation in the northern hemisphere was increasing in the summer and decreasing in the winter reaching extreme values *ca* 9,000 years ago; the insolation *ca* 18,000 years ago was similar to that today. The result was increased summer and lower winter temperatures *ca* 9,000 years ago (Huntley, 1991) whereas before *ca* 10,000 years ago a cold climate is evident by the presence of *Dryas octopetala*, dwarf Birch and Willow (Godwin, 1975). The early post glacial saw an increasing number of plant species appearing, presumably immigrating from the Continent via land bridges. As the climate warmed sea level rose initially cutting off Ireland from Britain and eventually Britain from the mainland of Europe. As trees and shrubs began to spread, sub-arctic species which were present during the last glaciation were displaced by the forest vegetation of the Preboreal period as a response to the increasing warmth.

2.2 The Present Climate

The accumulated effect of the daily weather conditions governs the geographic ranges of plant species; its affects are felt both directly and indirectly. Directly the climate determines the ability of a species to survive, and how well it can do this. Indirectly the climate effects the edaphic environment and also the ability of all other competing species to survive. Plant ranges and climate do not give a precise indication of a species range but show a general relationship between distribution and specific climatic factors.

Temperature is one of the principal aspects of climate influencing a species distribution. The summer temperature maximum has the sun as the dominant controlling factor; there thus is a progressively lower temperature maximum in the north due to the increased latitude. Interior regions contrast with coastal areas; in clear settled weather the temperature of the interior regions will rise rapidly during the day and fall quickly at night. The coastal areas show less of a diurnal temperature change due to the effects of the sea. The summer maximum temperature probably more or less directly limits the southward range of many northern plant species. The winter temperature minimum, usually in January, is beneficially influenced by the surrounding seas: overall minimum temperatures are much higher in maritime areas in continental areas at equivalent latitudes. Coastal regions of the British Isles are warmer than inland areas; there is also an east west trend, western coastal regions being influenced by the Gulf Stream current. Although winter temperature minimum is not likely to be the only factor involved, it probably has an influence in limiting the northward range of the more tender southern species. In addition there is a rapid fall in temperature with a rise in altitude. Allowances must also be made for local effects, such as shelter amongst the hills, together with areas of better drainage and aspect.

Frost occurs in nearly all parts of the British Isles, although the frequency and severity varies widely. The most frost free areas occur around the extreme west Atlantic periphery; away from this region the occurrence of frost increases rapidly with altitude and latitude. The most severe frosts in the British Isles probably occur in the eastern Scottish Highlands, the record minimum temperature was recorded at Braemar. Local topography may also influence the severity of frost, the mean minimum temperature being lower in well sheltered "frost hollows" than on nearby windy slopes. Prolonged exposure to frost can cause damage not only by cold but also through desiccation, especially if accompanied by wind. It is probably frost which restricts the eastern range of western species which are unable to tolerate temperatures that are continuously or extremely low. The low maximum temperatures found in the oceanic climates of the western fringes do not exceed those of the higher mountains in the interior regions and this enables some of the more typical montane species to descend to low altitudes near western coasts especially in the west of Scotland and Ireland.

Precipitation, like temperature, is a principal factor influencing plant distribution. The pattern of rainfall in the British Isles varies, showing both an increase westward and with ascending altitude. During the winter months, precipitation may fall as snow which tends to be greater in quantity and more frequent over high ground. The duration of snowlie increases with rise in altitude, latitude and distance from the west coast. An important effect of snowlie on vegetation where frosts are severe is that of insulation. It protects the vegetation from the fluctuating atmospheric temperature at the surface. The frequency of rainfall probably gives a better "biological index" of the effective wetness of the climate, especially for humidity sensitive species e.g. *Hymenophyllum* spp., than does the total amount of rain falling.

High frequency of rainfall is also associated with high frequency of cloud cover which results in reduced insolation. Cloud cover increases both westward and northwards and influences the general temperature by preventing the penetration of sunlight during the day and protects against heat loss at night. Frequent cloud cover and precipitation increase the humidity, which is further increased near the coast due to the Oceanic effect. Some plant species, in particular pteridophytes, are sensitive to direct sunlight; such plants have photosynthetic mechanisms which reach greater efficiency in conditions which are semi-screened. It is possible that both intensity and quality as well as duration of sunlight affect the distribution of plant species.

The average rate of evaporation of moisture from plant surfaces varies widely within the British Isles and with seasons, and is influenced by the relative humidity. Potential water deficit is a measure of the difference between rainfall and the potential evapotranspiration from the surface of vegetation. The pattern of the summer water deficit varies, the smallest deficit being in the upland areas in the west of the British Isles.

2.3 Geographical Zones of Plant Growth

Plant distribution patterns are partially based on their physiological reaction to ecological factors and consequently to a considerable extent on climate. Each species has its own particular geographical distribution pattern. J.R.Matthews (1937) suggests that while the climate is probably the controlling factor in determining the general distribution of species, it is not unlikely that many are able to exist towards the boundaries of their range because of the combined effects of climate and edaphic conditions. The physiological attributes which are most significant in affecting plant distribution are water, temperature and light.

World wide, plants are described as having a continuous or discontinuous range. The continuous range is intercontinental, and may be cosmopolitan having distribution all over the globe. It may also be circumpolar, having a distribution around the North or South Pole. Such plants tend to be easily dispersed and less exacting in their habitat range. Circumboreal plants are distributed around the top of the World in the boreal zone. Discontinuous ranges are interrupted, the Arctic-alpine plants are distributed in the arctic and in mountains of temperate or warmer zones. North Atlantic plants are distributed in Europe and North America and sometimes locally in Asia. Relict species are remnants of an earlier flora that has been "left behind" when the surrounding areas have been vacated by that flora.

Matthews (1937) classified the plants of Britain into elements upon the basis of their wider distribution patterns. The Continental Northern element includes species whose main area of distribution in Europe is central and northern. The species found in the British Isles are boreal, having their main area south of the arctic region. The varying latitude range distribution of different species in northern Europe is perhaps an expression of differing temperature requirements. The majority are perennials and in Britain the distribution falls roughly into two groups. Those which have a horizontal southern limit are fairly uniformly distributed, being more abundant in the north than the south. This was suggested by Salisbury (1926) to be due to the lowering of the water table in southern England. The other group have a northeast to southwest southern limit extending from the Humber to the Bristol Channel. The majority of these plants are found in wet habitats and their distribution indicates a tolerance of the climatic conditions of the north and west.

The Northern-Montane element consists of species of northern Europe that are generally absent from the low-lying plains but reappear in montane or subalpine situations in central or southern Europe. The distribution is markedly discontinuous and divided into northern and southern sections. In the north most of the plants are generally diffused but in central and southern Europe they are found in widely separated localities. In the British Isles the closest phytogeographic relationship is with Scandinavia, where all the species are found and nearly all have no northern limit. In Britain the distribution is in the north and mountain districts; most are upland, although a few descend almost to sea level. The plants of wet habitats favour the acid soils of the north and west, while the others are calcicole and prefer drier habitats.

The species found in the Arctic-Subarctic element are exclusively northern and are absent from central Europe, having their chief continental area lying north of the Baltic. In the British Isles there are thirty species of which only three occur south of latitude 50°N. The element is boreal and circumpolar. All the species are perennial and live a precarious existence; the individual life of most of them is probably relatively short.

The Arctic-Alpine element are plant species which are frequently circumpolar and their chief area of distribution lies in the Arctic, north of the tree boundary, and further south at relatively high altitudes in the mountains of Europe. In Britain a few species ascend to the summit of some of the higher fells i.e. over 1216 m, where they are exposed to very severe environmental conditions. The majority do not usually descend below 600 m except along the sides of streams, although in the north of Scotland and in Ireland some occur at sea-level. Marked discontinuity is the outstanding feature of these plants; although in polar regions they are generally spread, further south invariably they occur isolated in detached colonies. In Britain no other element shows such marked discontinuity in distribution. Matthews (1937) states that fully fifty percent of the British species are plants of dry habitats or well drained soils, whereas the remainder require a considerable degree of moisture during the growing season. Of the numerous factors which have led to the existing distribution of this element in Britain, climatic changes are perhaps the most important. There is a considerable diversity of ecological type and the complex of environmental factors is not likely to have affected all the species alike.

2.4 Possible changes in the climate due to global warming

The forecast change in the climate is due to an increase in greenhouse gases in the atmosphere. The greenhouse gases include carbon dioxide, methane, chlorofluorocarbons and related gases, nitrous oxide and water vapour; these have all increased substantially since the Industrial Revolution. The action of greenhouse gases is to cause infra-red radiation to be retained in the atmosphere so causing the Earth's surface and the lower atmosphere to warm up.

Predictions made using Atmospheric General Circulation Models (GCM's) indicate a global average rise in temperature of between 1.5°C and 4.5°C for an effective doubling of carbon dioxide over preindustrial levels (Mitchell *et al.*, 1990). If the emissions of greenhouse gases continue at the rate of 1990 this situation will arise in 2030 approximately. Water vapour is the most abundant of the natural greenhouse gases and will increase due to higher rates of evaporation resulting from the higher temperature. Carbon dioxide also occurs naturally and without it the Earth's surface would be 35°C lower and hostile to life as we know it today.

GCM simulations predict that surface air will warm faster over land then over oceans and warming will occur around Antarctica and in the northern North Atlantic region. Precipitation is predicted to increase on average in the middle and higher latitude continents in winter by some 5-10% between 35°-55°N. The number of days with a minimum threshold amount of soil moisture would be sensitive to change in the average precipitation and evaporation. Changes in the variability of weather and the frequency of extremes, such as very hot days or frosty nights, may have more impact then changes in the mean climate at a particular location.

Houghton *et al.* (1992) present the results of new GCM simulations that modify some of the predictions made by Mitchell *et al.* (1990). Warming over parts of the Northern Hemisphere and mid latitude continents over the last few decades has been due to an increase in night-time rather than day-time temperatures. These changes appear to be particularly related to increase in cloudiness although other factors such as the direct cooling effect of aerosols on maximum temperatures in sunny weather cannot be ruled out. A small, irregular, decrease of approximately 8% has been noted in annual average snow cover over the Northern Hemisphere since 1973. It has also been shown that the global warming trends show regional and seasonal diversity and not every region shows warming.

It is predicted that due to global warming the atmosphere will contain more water vapour due to increasing rates of evaporation. In the warmer world ice and snow in mountain glaciers and polar regions will melt. This will reduce the effects of solar radiation back into space as dark surfaces will absorb more radiation, this will mean a positive feedback. The full extent of this phenomenon needs more work so the total effect can be understood. The effects of changes in cloud cover and radiative consequences probably are the biggest uncertainty. The nature and altitude of clouds can have both positive and negative feedbacks in global warming. In the modern world the overall effect of clouds is to cool the Earth. The change in climatic patterns will also involve changing wind patterns world wide.

CHAPTER 3

Selected Plant Species

The overall ranges of the native plants in the British Isles are determined by a complex of many different factors that includes historic, topographic, edaphic and climatic. These factors can be broken down into many different components and then recombined in different ways to influence plant growth. The plants selected for this investigation are species of Pteridophytes and Angiosperms that are restricted to the northwest of the British Isles, their southern limits run diagonally from the southwest to the northeast, a boundary that was stated by Salisbury (1932) to be essentially determined by climate. The effect of climate on different species varies widely; the limiting factor for a particular species may not be the same throughout its range and in many cases a combination of factors is involved.

In Ireland, lands above 305 m elevation are not extensive and are around the periphery; only scattered summits exceed 760 m. On the British mainland there is a general increase in altitude northward and westward. Most of the land above 305 m is found in Devon, Wales, the Pennines, the Lake District and throughout Scotland. Areas exceeding 760 m are found in North Wales, the Lake District and the Scottish Highlands. The rate at which temperature falls with increasing altitude is about 1.1°C per 200 m. The distribution of mountain masses strongly influences the climate, in some areas creating habitats for "alpine" species. In addition to a tendency for these species to descend to lower altitudes at more northerly latitudes, there also is a tendency for "alpine" species to descend to lower altitudes in a western parts of the British Isles, the lack of hot summer conditions perhaps enabling the plants to survive. As these oceanic conditions influence to a greater or lesser extent the climate of most of the British Isles, species which typically grow at high altitude in the continent of Europe grow at a lower level in the British Isles.

The Danish botanist Raunkiaer (1934) classified plants according to the position of their resting buds or persistent stem apices in relation to soil level. These classes indicate how plants survive unfavourable weather conditions and their distributions show a correlation with climate. Phanerophytes are woody plants with buds more than 25 cm above the soil level. Chamaephytes are woody or herbaceous plants with buds above the soil surface but below 25 cm. Hemicryptophytes are herbs with buds at soil level. Geophytes are herbs with buds below the soil surface. Therophytes are plants which pass the unfavourable season as seeds. Hydrophytes grow in water and Helophytes are marsh plants (Clapham *et al.*, 1989).

The Latin names for the plant species are those in "*Flora Europaea*" (Tutin *et al.*, 1964, `68, `72, `76, `80), and the English names in the "*Flora of the British Isles*" (Clapham *et al.*, 1989).

3.1 Pteridophytes

These plants have an alternation of free-living generations. The sporophyte generation is dominant. It has vascular tissue and reproduces by the production of spores. These spores give rise to a small filamentous or thalloid gametophyte. The gametophyte generation bears archegonia and antheridia either on the same or different prothalli. Moist conditions are essential for fertilisation as the antherozoids, male sex cells, are motile. The new sporophyte generation develops from the fertilised archegonia on the prothallus.

Much of the general information about Pteridophytes used in the following accounts is derived from Page (1982, 1988).

3.1.1 ***Lycopodium annotinum*** (Interrupted Clubmoss) is a mountain plant, occurring usually above 455 m, in the British Isles, often much higher, and scarcely ever descending to the lower valleys as do other mountain clubmosses. It is a strongly calcifuge plant, growing on heaths, moors and mountain grassland, although seldom in any abundance. It favours sites that are damp; these include sheltered pockets in heather moorland on peat over fluvio-glacial moraine as well as peaty mountain slopes, hollows and stream banks over predominantly acid rocks. The sporophyte is relatively large with aerial shoots arising from surface-creeping, rooted perennial stems. Spore bearing "cones" arise at the short tips (Page, 1982).

3.1.2 ***Isoetes lacustris*** (Quillwort) is adapted to a wholly submerged existence. It is rooted to the bottom of lakes, although the water depths in which it occurs in the British Isles vary widely with the clarity of the water. In the mountainous regions of northern Britain it grows on the submerged bottoms of acidic, clear-watered upland lakes and tarns, at a depth of 1-6 m, where there is a slight current and some wave action. The plants are perennial and usually are gregarious. Differences observed between plants from different lakes may reflect genetic differences between populations, those of different lakes representing isolated inbreeding populations. Spores may be dispersed by wind and birds such as ducks. It can grow well in eutrophic waters but is naturally excluded from these by the density of competitors. A viviparous form has been reported to occur in Lake Windermere (Page, 1982).

3.1.3 ***Equisetum pratense*** (Shady Horsetail) is a northern species with scattered stations in the British Isles. Seldom found in great abundance, it is essentially a pioneer plant. Thriving particularly on deep, moist but freely-draining banks of essentially sandy soils, where there is a relatively high base-status. The plants demand permanent soil moisture and high air humidity developing best where there is light shade from summer desiccation; in cloudy regions extending into open habitats, especially on mountains. In closed turf vegetation it often occurs as sparse diminutive shoots, and probably represents a relatively late seral stages in which the horsetail is steadily succumbing to competition from angiosperms. In northern areas of the British Isles it succeeds vegetatively its reproductive capacity being in a delicate state of balance, as the strobilus production is poor and sporadic. The vegetative stems are 10-30 cms in length, underground there are creeping rhizomes (Page, 1982).

3.1.4 ***Hymenophyllum tunbrigense*** (Tunbridge Filmy-fern) is a western Atlantic species, in the British Isles it is generally more abundant at lower altitudes and seems to be confined to sites below 90 m in Scotland, 580 m in Wales and 412 m in Devon, above these altitudes, it becomes replaced entirely by populations of *H.wilsonii* (Page, 1982). It is a gregarious fern, with a creeping rhizome, usually occurring as numerous nearby, discontinuous patches; growing amongst moist, shaded, rocky outcrops, in well-wooded, sheltered, stream valleys and in deep rocky stream gorges. It thrives on freely-drained, steep or vertical rock surfaces, with the fronds mostly in a hanging position. The gametophyte and sporophyte stages are both intolerant of desiccation; growing where it is shaded from summer sun and sheltered from frost and desiccating winter winds. It is probable that temperature restricts its northern and upper altitude limit, perhaps by an insufficient average number of day-degrees above some threshold value. No British locality has a mean July temperature of more then 17°C or mean maximum of more then 22°C. The mean January temperature at all British localities is probably above 3.9°C and mean minimum above 1°C. All British localities (except Sussex) have an annual rainfall of 1000 mm or more and the majority over 1500 mm and at least 225 rainy days. All areas (except Sussex) have less then 76 mm water deficit. The drought resistance of its gametophyte is very low, when contrasted with ***H.wilsonii.*** It also has a lower compensation point than *H.wilsonii* which explains its greater tolerance of poorly illuminated sites (Richards & Evans, 1972).

3.1.5. ***Hymenophyllum wilsonii*** (Wilson's Filmy-fern), is a western Atlantic species, in the British Isles it is a more widely distributed than *H.tunbrigense* occurring in western situations from sea level to 1000 m. It is gregarious forming many nearby patches within deep ravines and river gorges, on the vertical faces of rock, tree trunks in valley woodlands or amongst scree on mountain sides. It is a more widely distributed species than *H.tunbrigense*; growing in moderate shade or in the open provided the atmosphere is not too dry. It is tolerant of low winter temperatures and it is unlikely that normal temperatures exceed its limits of tolerance anywhere in the British Isles. In all the areas in which it is found the rainfall exceeds 1000 mm a year with at least 200 rainy days. All sites are within an area with less then 76 mm annual average potential water deficit (Richards & Evans, 1972).

3.1.7 ***Dryopteris abbreviata*** (Mountain Male-fern) is restricted to mountainous districts of the British Isles where it occurs in scattered groups on well-drained rocky ledges or on open slopes of steep mountain scree, at 240-610 m. Its habitats are all in regions of high and frequent rainfall, with prolonged cloud cover. The bulky rhizome masses often become encumbered at the end of the season with a covering of old, dark-brown fronds, which persist until new fronds flush in the following spring. It is probable that the old, dark-coloured fronds form a heat-absorbing blanket, aiding the normal thermal balance of the plant (Page, 1982).

3.1.7 ***Polystichum lonchitis*** (Holly Fern) an arctic-alpine species which in the British Isles is rare and local in occurrence. The plants occur chiefly on lime rich rocks at about 610-915 m, descending very locally in a few, steep, cool upland valleys to about 150 m. Its range seems to correspond roughly to a maximum summer temperature of about 27°C. The rather slow rate of establishment and subsequent growth probably prevents Holly Fern from readily succeeding in the slopes of recent screes and rockfalls. It occurs chiefly amongst older, more stable, more serally mature scree slopes, in which it is probably eventually replaced by a blanketing angiosperm vegetation (Page, 1982).

3.2 Angiosperms

These are flowering plants in which the dominant sporophyte generation is free living. The ovules contain megaspores which are completely enclosed in the ovary. Fertilization is effected by means of a pollen tube, the microspores being contained within the pollen grains, which are non-motile. Self-pollination or pollination by insects or wind being necessary for sexual reproduction.

Much of the general information about the Angiosperms used in the following accounts is derived from Clapham *et al.* (1989).

3.2.1 *Thalictrum alpinum* (Alpine Meadow rue) is an arctic alpine (Matthews, 1937) perennial. In the British Isles it ascends to 1213 m as well as descending to sea-level in the north west. It is a stoloniferous herb with a short slender rhizome occurring on limestone rocky slopes and mountain ledges. The flowers are hermaphrodite and wind pollinated. It survives adverse weather climatic conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.2 *Subularia aquatica* (Awlwort) is a northern montane (Matthews, 1937) annual or biennial aquatic herb. In the British Isles it thrives submerged to a depth of 60 cm where the water is clear. It is unable to tolerate peaty materials, long exposure out of water, or running water. It can however survive for short periods on shingle when lake levels are low. The flowers are produced on leafless stems, and set seed whether totally submerged or temporarily in terrestrial conditions. The submerged flowers are self-pollinated while they are closed, the terrestrial flowers are pollinated by insects. It is able to survive unfavourable climatic conditions as a therophyte. As there is no means of vegetative propogation it does not spread freely (Woodhead, 1951).

3.2.3 *Draba incana* (Hoary Whitlow Grass) is an arctic alpine (Matthews, 1937) biennial or perennial herb. It is a calcicole which is found on screes, cliffs, rocks, gullies, mine heaps and sometimes open turf. In the British Isles it grows from sea-level to 1080 m (Clapham *et al.*, 1989). It is very variable, each population differing slightly (Rich, 1991). The distribution in Ireland, Scotland and Isle of Man is within the 23°C maximum summer temperature summit isotherm and in England and Wales is within the 26°C isotherm (Conolly & Dahl, 1970). It has a slender tap-root with a short prostrate, occasionally branched stock bearing the remains of dead rosettes. The erect flowering stems may be simple or branched, varying in height from 7-50 cm. The flowers are self-pollinated. It survives unfavourable weather conditions as a chamaephyte (Clapham *et al.*, 1989).

3.2.4 *Silene acaulis* (Moss Campion) this has an arctic alpine (Matthews, 1937) distribution. In the British Isles it grows on cliffs, ledges, scree and summit detritus of mountains; also down to sea level on cliffs, rocks and stabilised sand-dunes. In the southern part of its range it behaves as a calcicole; becoming increasingly abundant on poor acid rocks and soils from the Cairngorms northwestwards. In its more southerly habitats e.g. Snowdonia, it shows a marked preference for steep north and northeast facing cliffs, slopes and deep ravines, being intolerant of deep shade. Further north it is less restricted in its preference and often occurs on level or gently sloping ground. All localities in the British Isles lie within an average mean daily maximum of below 13°C at sea level. It is not certain that the difference in behaviour between the north and south of Britain can be explained by maximum temperature alone, minimum atmospheric humidity may be a contributing factor. Absence on south and west slopes in some of the more southern localities may be due to the infrequency of suitable damp base-rich rocks with these aspects. The majority of localities are in areas which have an annual rainfall of over 1250 mm. It is a densely tufted and much branched forming a moss-like cushion 2-10 cm high, with a tap root. The flowers may be hermaphrodite, or male and female, the pollinators are insects. It is never dormant, being resistant to frost; it survives adverse conditions as a chamaephyte. The distribution pattern in the British Isles suggests it probably has only limited drought resistance (Jones & Richards, 1962).

3.2.5 *Geranium sylvaticum* (Wood Crane's-bill) has a continental northern (Matthews, 1937) distribution. In the British Isles it grows in meadows, hedgebanks, damp woods and mountain rock ledges, ascending to about 1060 m. It is a perennial herb with a stout rhizome. The flowers are pollinated by insects, and the fruits are dehiscent. The unfavourable season is passed as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.6 ***Vicia orobus*** (Wood Bitter Vetch) is scattered very locally throughout the British Isles although rarely found in Ireland. It is a perennial, with an erect stout stem, growing in rocky and wooded places. The flowers have nectar and are cross-pollinated by bees, the fruits are dehiscent. The unfavourable season is survived as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.7 *Rubus saxatilis* (Stone Bramble) is a northern montane (Matthews, 1937) stoloniferous perennial herb. In the British Isles it is local, growing in stony woods and on shady rocks in hilly districts. The flowering stems are annual, the much longer non-flowering stems are procumbent, producing axillary branches which root at the tips. The flowers are visited by bees and flies, self pollination may also occur (Clapham *et al.*, 1989).

3.2.8 *Rubus chamaemorus* (Cloudberry) a subarctic (Matthews, 1937) perennial herb with short creeping rhizomes having the over wintering buds. The distribution has an eastern bias in the British Isles particularly in the more southern part of its range. It is characteristic of blanket bog vegetation, occurring on level or gently sloping ground which is suitable for the formation of ombrogenous peat. It is limited, both climatically and topographically, to areas of low potential water deficit, the distribution map corresponding closely with areas of low water potential deficit (Green, 1964). It behaves as a shade plant. The flowering stems are annual erect and 5-20 cm long with strictly dioecious flowers, the male flowers producing nectar. Pollination is by insects and the fruits are dispersed by birds (Taylor, 1971).

3.2.9 *Potentilla fruticosa* (Shrubby Cinquefoil) is a northern montane (Matthews, 1937) dioecious, deciduous shrub. In the British Isles it is confined to three areas: Teesdale, the Lake District and the west of Ireland. The altitude range is from 15-650 m. There are two distinct climatic regions, lowland in Ireland and upland in the Lake District and Teesdale. Rainfall is high in all areas but there are differences in temperature; in Teesdale (Moorhouse) the mean temperatures for January and July are 0.5°C and 13°C respectively, in Ireland (Ballyrough) they are 5.8°C and

14.4°C. It appears to be unaffected by frost; in Ireland frosts and snow are rare in Teesdale they are frequent. It tolerates extreme conditions preferring intermittently wet unshaded ground on basic rocks. In Ireland and Teesdale the sites are liable to flooding (Elkington & Woodell, 1963). The flowers are visited by insects. It survives unfavourable conditions as a phanerophyte (Clapham *et al.*, 1989).

3.2.10 *Potentilla crantzii* (Alpine Cinquefoil) is an arctic alpine (Matthews, 1937) perennial herb. In the British Isles growing from 80-1025 m on mountain rock ledges, crevices, and occasionally on grassland, usually on basic soils. The stock is thick, emitting short branches which scarcely ever root and never form mats. It is apomictic but pollination is necessary for the development of seeds. Survives the unfavourable season as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.11 *Dryas octopetala* (Mountain Avens) this is an arctic alpine (Matthews, 1937) plant. The populations in the British Isles are variable in leaf size, which is genetically controlled. It grows from sea-level to a height of 1050 m the distribution being primarily linked by climatic factors and secondarily by its edaphic requirements. The distribution map shows the sites are all included within the 25°C isotherm and in Scotland bounded by the 23°C isotherm. All localities in the British Isles are in areas with an annual rainfall exceeding 1000 mm a year and the majority are within an annual average potential water deficit of less then 25 mm, all being in areas of less than 50 mm. It is restricted to sites with free drainage where considerable water deficits may exist at times and the effect of increased summer temperatures may be through increasing water stress. It is typically a pioneer species restricted to open, non-shaded sites or on slopes of any aspect. It is a calcicole growing on a wide range of calcareous rocks. It is completely resistant to frosting and damage due to drought has not been observed. It is a much branched, tortuous creeping dwarf perennial shrub, with a stout, woody root stock. The flowers are visited by various insects, self-pollination is also possible; the fruits are wind dispersed, vegetative reproduction is limited (Elkington, 1971). It survives unfavourable seasonal conditions as a woody chamaephyte (Clapham *et al.*, 1989).

3.2.13 *Alchemilla alpina* (Alpine Lady's-mantle) is an arctic alpine (Matthews, 1937) plant, in the British Isles it ascends to over 1215 m and descends almost to sea level; growing in mountain grassland, rock crevices, screes and mountain tops. In the southern part of its range it grows as a calcifuge. A perennial herb which has a short creeping stock that is woody, rather thick and branched. The flowers are pollinated by insects. Survives during the unfavourable season as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.13 *Rhodiola rosea* (Rose Root) is an arctic alpine (Matthews, 1937) plant in the British Isles it grows in the crevices of mountain rocks, ascending to 1175 m, in the west of Scotland and Ireland it occurs on sea cliffs. It is a dioecious perennial plant, with a stock that is thick fleshy and branched, projecting above the ground level. The flowers are visited by flies. It survives unfavourable seasons as a protohemicrytophyte (Clapham *et al.*, 1989).

3.2.14 *Sedum villosum* (Hairy Stonecrop) has a continental northern (Matthews, 1937) widespread, but rather local, distribution. In the British Isles growing on streamsides and wet stony ground, ascending to 1100 m. It is a small, perennial sometimes biennial plant, with an erect stem, often branched at the base, the branches may be sterile or flowering. It survives the unfavourable season as a chamaephyte (Clapham *et al.*, 1989).

3.2.15 *Saxifraga nivalis* (Alpine Saxifrage) is an arctic alpine (Matthews, 1937) plant. In the British Isles it is usually rare and very local. It occurs on wet rocks, on mountains from 365-1310 m. A perennial herb, which has a short thick stock, the flowers are pollinated by insects. Survives adverse climatic conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.16 ***Saxifraga stellaris*** (Starry Saxifrage) an arctic alpine (Matthews, 1937) plant which in the British Isles ascends to 1343m; it is common on mountains, by streams, in springs, on wet rock ledges and wet stony ground. It is a perennial herb with short stock, the flowers are visited mainly by flies, although pseudoviviparous plants are known to occur in west Galway. It can survive adverse climatic conditions as either a hemicryptophyte, or a chamaephyte (Clapham *et al.*, 1989).

3.2.17 ***Saxifraga aizoides*** (Yellow Saxifrage) is an arctic alpine (Matthews, 1937) plant. In the British Isles it ascends to 1175 m and is found on streamsides and wet stony ground on mountains. A perennial herb with a basal rosette, the flowers are usually pollinated by flies. It survives unfavourable climatic conditions as a chamaephyte (Clapham *et al.*, 1989).

3.2.18 ***Saxifraga oppositifolia*** (Purple Saxifrage) is an arctic alpine (Matthews, 1937) plant. In the British Isles the species varies in its growth habit from loosely creeping to densely tufted. It is locally abundant, on base-rich rocks and stony ground at medium to high elevations, most sites are above 300 m although it descends to sea level in Scotland. The habitats are more or less fully exposed to sun, it seems to be intolerant of intense shade. At its more southerly habitats the growth is chiefly on north facing slopes. Snow cover is not needed, and most of the localities are partially sheltered from strong winds. Its absence from the tops of mountains is doubtless due to the fact that basic rock ledges and flushed slopes do not extend to summits and not a climatic factor. Nearly all localities are in areas of high rainfall, the majority are over 1500 mm a year and have high humidity. Dahl suggests intolerance of high summer temperatures is one of the chief limiting factors for its distribution in Scandinavia. It is intolerant of competition and is rarely or never found in close plant communities. Adventitious roots which arise on the lower side of the creeping shoots make it possible for portions of the plant to survive when accidently broken off. The flowers are insect pollinated but are often self pollinated (Jones & Richards, 1956). The plant survives adverse conditions as a chamaephyte (Clapham *et al.*, 1989).

3.2.19 *Epilobium anagallidifolium* (Alpine Willow-herb) is an arctic alpine (Matthews, 1937) plant. In the British Isles it grows by streams and springs on mountains, from about 155-1220 m. It is a perennial alpine herb, ascending from a decumbent base, the flowers are probably self-pollinated, the fruits are dehiscent with seeds that are wind dispersed. It survives the unfavourable conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.20 *Epilobium alsinifolium* (Chickweed Willow-herb) is an arctic alpine (Matthews, 1937) plant which in the British Isles grows by streams and springs on mountains from 122-1100 m. It is a perennial alpine herb, ascending from a decumbent base, the flowers are probably self-pollinated, the fruits are dehiscent with seeds which are wind dispersed. It survives unfavourable weather conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.21 *Meum athamanticum* (Spignel) is a continental northern (Matthews, 1937) plant growing in grassy places in the mountainous districts of the British Isles. It is a tufted branched perennial, the stock having abundant coarse fibrous remains of the old petioles. Most of the flowers are hermaphrodite, although male flowers do occur, pollination is by insects. It survives adverse weather conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.22 *Polygonum viviparum* (Alpine Bistort) is an arctic alpine (Matthews, 1937) plant which in the British Isles grows from sea level to 1350 m in Scotland. On wet alpine rocks, consolidated screes and grassland, it may be carried by streams down to lower pastures. A perennial with a rather stout rhizome which is bulb like at the base. The flowers in the upper part of inflorescence are pollinated by insects but seeds are rarely set. Vegetative reproduction is by bulbils which are distributed by birds and wind (Lousley & Kent, 1981). It survives in adverse weather conditions as a protohemicryptophyte (Clapham *et al.*, 1989).

3.2.23 *Oxyria digyna* (Mountain Sorrel) is an arctic alpine (Matthews, 1937) plant which in the British Isles grows up to over 1200 m on damp rocky ledges and occasionally on screes and by mountain streams. It may be carried downstream to river shingle at sea-level (Lousley & Kent, 1981). All the sites in Ireland, Scotland and the Isle of Man are within the 23°C maximum summer temperature isotherm, the sites in England and Wales are within the 24°C isotherm. (Conolly & Dahl, 1970). It is a tufted perennial, which has a woody rootstock, and dioecious flowers, the fruits are winged. It survives unfavourable conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.24 *Salix phylicifolia* (Tea-leaved Willow) is a northern montane (Matthews, 1937) plant which in Britain is commonly found on carboniferous limestone, it is very rarely found in Ireland. It has been recorded from near-sea level up to 670 m on moist rocky ground. A dioecious plant which is a robust low spreading deciduous shrub or small tree 2-3 m high. Pollination is carried out by insects (Meikle, 1984). It is able to survives unfavourable conditions as a nanophanerophyte (Clapham *et al.*, 1989).

3.2.25 *Salix herbacea* (Dwarf Willow) is an arctic alpine (Matthews, 1937) plant which grows in the British Isles on moist exposed ledges, rocky summits, or with grasses and sedges, usually from between 610 and 1310 m. In Shetland it grows at 150 m (Meikle, 1984). It is a perennial shrub with a long creeping branched rhizome. In exceptionally sheltered sites, on moist screes, the stem can exceed 6 cm in length. The flowers are dioecious with nectaries, and are insect pollinated. In adverse conditions it survives as a chamaephyte (Clapham *et al.*, 1989).

3.2.26 *Utricularia intermedia* (Intermediate Bladderwort) is a continental northern (Matthews, 1937) plant which in the British Isles is very local, growing in lakes, pools and ditches, usually in shallow peaty water, it ascends to 990 m (rare at high altitudes). It is a perennial rootless herb overwintering by turions. Very rarely flowering the stems are slender, 10-25 cm long, and of two kinds; they may bear green leaves without or occasionally with very few bladders, or be colourless, bearing bladders on very much reduced leaves (Clapham *et al.*, 1989).

3.2.27 ***Galium boreale*** (Northern Bedstraw) this is a continental northern plant (Matthews, 1937) which in the British Isles grows on rocky slopes, moraine, scree and shingle, the sides of streams and lakes, also stable sand dunes, ascending up to 1060 m in Scotland. It is a perennial herb with a creeping root stock and an erect, rigid stem. The hermaphrodite flowers are visited by various small insects. It survives unfavourable weather conditions as a protohemicryptophyte (Clapham *et al.*, 1989).

3.2.28 ***Cirsium helenioides*** (Melancholy Thistle) is a continental northern (Matthews, 1937) plant which grows in the British Isles from 90-975 m in hilly pastures, on stream-sides, upland scrub and open woodland. It is a perennial stoloniferous herb with an obliquely ascending stock, the flowers are visited by bees, the seeds are wind dispersed. It survives adverse climatic conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.29 ***Saussurea alpina*** (Alpine Saussurea) this is an arctic alpine (Matthews, 1937) plant which in the British Isles has an altitude range from 46-1190 m growing on mountain rocks, scree and maritime cliffs. It is a perennial herb with a stock which produces short stolons, the fragrant flowers are pollinated by flies and bees, the fruits are wind dispersed. It survives unfavourable conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.30 ***Pseudorchis albida*** (Small White Orchid) is a northern montane (Matthews, 1937) plant which grows usually in rough but well-drained grassy meadows and pastures, especially in the hilly districts of the British Isles. It is tolerant of both calcareous and non-calcareous soils. A rare plant which is becoming more frequent further north, especially in northwest Scotland and the Inner Hebrides. The root-tubers are deeply palmate, and the flowers are probably cross-pollinated by tiny insects (Clapham *et al.*, 1989).

3.2.31 ***Sparganium angustifolium*** (Floating Bur-reed) has a continental northern (Matthews, 1937) distribution growing in peaty lakes, mainly in mountainous districts being widely distributed in the north and west of the British Isles. It is a rhizomatous perennial aquatic herb. The flowers are unisexual and wind pollinated (Clapham *et al.*, 1989).

3.2.32 ***Carex magellanica*** (Bog Sedge) this is a northern montane (Matthews, 1937) plant which is rare in the British Isles. It occurs in oligotrophic mires, being unable to tolerate standing water. Its favourite habitat being a level ledge, near the crest of a moor. It is a perennial with short creeping rhizomes, the flowers are monoecious, which are variously arranged in the inflorescence, and are wind pollinated (Jermy, 1982).

3.2.33 ***Carex bigelowii*** (Stiff Sedge) is an arctic alpine (Matthews, 1937) plant which in the British Isles occurs above 600 m for most of its range in wet corries and ledges, in flushed gullies it can become a robust plant. It is a perennial with short creeping rhizomes, the shoots are solitary or in pairs. The flowers are monoecious and are wind pollinated (Jermy, 1982). It survives unfavourable climatic conditions as a hemicryptophyte (Clapham *et al.*, 1989).

3.2.34 ***Carex pauciflora*** (Few-flowered Sedge) this is an arctic alpine (Matthews, 1937) species of oligotrophic bogs on wet moors, becoming less frequent in the east of the British Isles. It is a perennial with a slender rhizome that is short and creeping, often much branched forming an open mat. The shoots are loosely tufted, with flowers that are monoecious and wind pollinated (Jermy, 1982).

CHAPTER 4

Distribution Maps and Response Surfaces

4.1 Method

The "*Atlas Florae Europaeae*" (AFE) (Jalas & Suominen, 1972, '73, '76, '79, '80, '83, '86, '89, '91) was initially searched to find which of the species had been mapped by "The Committee for Mapping the Flora of Europe, and Societas Biologica Fennica Vanamo" in Helsinki. The AFE uses a 50 km Universal Transverse Mercator (UTM) grid to record distributions, Europe comprises *ca* 4400 squares. The maps for the remaining species were manually prepared based on the AFE 50 km UTM grid; these are referred to as the non-AFE distributions (NAFE). The sources used were "*Atlas of the British Flora*" (Perring & Walters, 1990) "*Atlas of the Distribution of Vascular Plants in North West Europe*" (Hultén, 1950) "*The Amphi-Atlantic Plants and their Phytogeographical Connection*" (Hultén, 1958) "*The Circum-polar Plants Vols. I & II*" (Hultén, 1962, 1970) "*Vergleichende Chorologie der zentraleuropäishen Flora Band I, II, & III*" (Meusel *et al.*, 1965, 1978, 1992). Arc-info programmes were made available so that the distribution of each species could be transcribed manually into a machine readable form.

Response surfaces were prepared, using climatic data (Wolfgang Cramer, unpublished). Three bioclimatic variables only were used, they were the Mean Temperature of the Coldest Month (MTCO), the Growing Degree Days above a 5°C threshold (GDD5) and an estimate of the ratio of actual to potential evapotranspiration (AET/PET) (Prentice *et al.*, 1992). Response surfaces were fitted, using the 4419 UTM grid cells, the bioclimate values being for the mean altitude of the grid cell in question, and the presence or absence of the species. These surfaces express the probability of the species occurring at a given location in the climatic space.

No smoothing of the fitted surface took place; smoothing makes the surface simple to comprehend visually, and initially was considered to be the method to be used. It was found, however, that where the surfaces were smoothed the simulated distributions matched the recorded distributions less well than when unsmoothed. This is thought to be due to the fact that in nature the edge of the range in which a plant exists is not distinct due to the interaction of the many factors which enable a plant to grow. The unsmoothed surface appears for the purpose of this study to give a much better representation of the species distribution than the smoothed surface and has been used throughout.

Having obtained the response surface for a species it was possible to simulate the likely occurrence of the species in a grid cell, giving a simulated distribution. This was carried out using present climatic conditions, and simulated distributions were obtained. A low degree of smoothing is inherent in the calculation of a response surface giving a low probability of occurrence of the species in some grid cells where the species has not been mapped. It was therefore necessary to determine a "threshold probability value" for each species. If this value is set too high, although the majority of the simulated occurrences will coincide with observed occurrences, many observed occurrences will not be simulated. If the value is set too low then, although most of the observed occurrences will be simulated, many of the simulated occurrences will not coincide with the observed occurrences. The best value was obtained by visual examination, comparing the original map and simulated maps using alternative thresholds.

Having obtained a simulated distribution for the present climate, any combination of the three bioclimatic variables can be substituted and a simulated distribution obtained. Two GCM scenarios for possible climatic change were fitted and the potential distribution of each species simulated. The scenarios used were the high sensitivity United Kingdom Meteorological Office 2 x CO_2 scenario (UKMO) (Mitchell, 1983) and the less sensitive Oregon State University 2 x CO_2 scenario (OSU) (Schlesinger, 1989). No GCM currently gives a realistic climatic scenario at a scale compatible with those at which we observe patterns in terrestrial ecosystems. It conventionally is believed that the magnitude of the relative changes between the control and 2 x CO_2 runs for any one GCM may be used to approximate the coarse-scale pattern of possible climate change (Webb *et al.*, 1987; Prentice *et al.*,1993). The anomalies between the control and 2 x CO_2 runs were used for each GCM. Temperature anomalies were expressed as differences whereas precipitation anomalies were expressed as ratios. The mean monthly temperature and precipitation anomalies was used to modify the values previously interpolated for each of the AFE grid cells from the meterological station data. The potential future distributions were obtained in a similar manner to the simulated present distributions, the GCM derived values for the three bioclimatic variables being substituted for the present day variables. The probability thresholds applied to these maps were the same as for the simulated present distribution.

4.2 Results

See Fig.4.0 for areas of Europe.

4.2.1 ***Lycopodium annotinum***: The response surface (Fig.4.1) shows the main distribution to be concentrated in areas with GDD5 values that are <*ca* 2600 day degrees and MTCO values of <2°C and there is little occurrence at AET/PET values <0.75.

The present simulation at a threshold probability of 0.35 (Fig.4.2b) matches well with the AFE distribution (Fig.4.2a) (Jalas & Suominen, 1972) the main discrepancy being a greater presence in Iceland and the Balkans. The simulated range for the OSU 2 x CO_2 climatic scenario (Fig.4.2c) shows a north and eastward movement, complete displacement from the British Isles, reduced presence in Iceland and presence in Svalbard. The UKMO 2 x CO_2 scenario (Fig.4.2d) shows a complete displacement from the mainland of Europe except for the Alps, northern Fennoscandia and northern Russia. It occurs in Iceland, Jan Mayen and Svalbard.

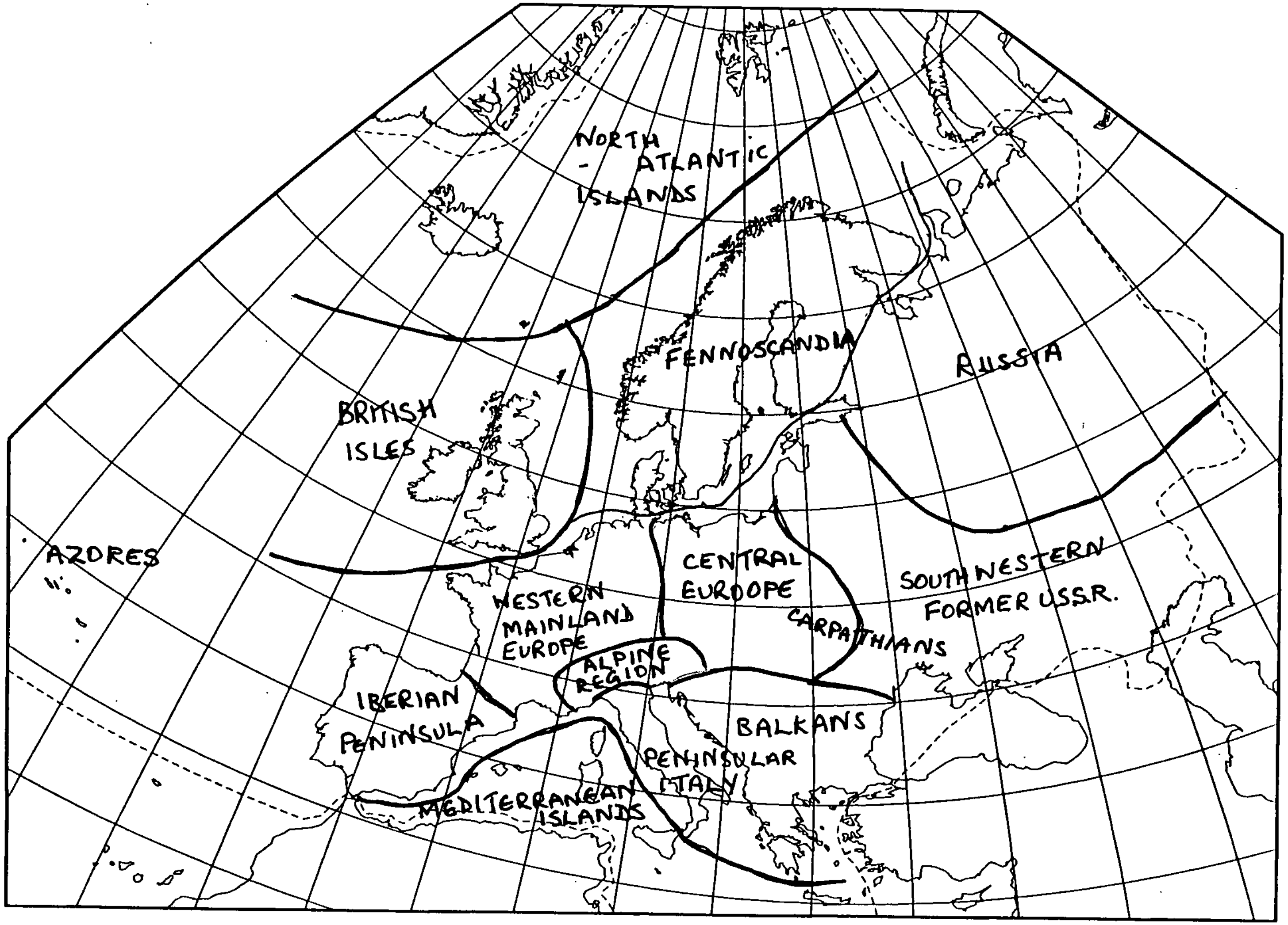


Figure 4.0 Areas of Europe

4.2.2 *Isoetes lacustris*: The response surface (Fig.4.3) shows limitations to be MTCO <6°C, with GDD5 <*ca* 2200 day degrees. The significance of the AET/PET value is doubtful as this plant occurs submerged in lakes and tarns.

The present simulation at a threshold probability of 0.40 (Fig.4.4b) compares very well with the AFE distribution (Fig.4.4a) (Jalas & Suominen, 1972) apart from a greater presence in the Alps and other mountain ranges that probably is due to the fact it grows in water, an aspect of its distribution not accounted for in the bioclimate data. The OSU 2 x CO_2 scenario (Fig.4.4c) shows a northward displacement, with occurrence in the north of Scotland, the Alps, Iceland, northern Fennoscandia and Russia. In the UKMO 2 x CO_2 scenario (Fig.4.4d) it is absent from the British Isles, occurring only in the Alps and the extreme north of mainland Europe, Iceland, Jan Mayen and Svalbard.

4.2.3 *Equisetum pratensis*: The response surface (Fig.4.3) shows the distribution to be mainly concentrated where the MTCO is <4°C and GDD5 <*ca* 2400 day degrees. There is a marked reduction in presence when the AET/PET <0.80, this shows the need for permanent soil moisture and a high humidity (see3.1.3).

The simulation for present climate was matched at a threshold probability of 0.5 (Fig.4.6b) with the AFE distribution (Fig.4.6a) (Jalas & Suominen, 1972). The main discrepancies were its absence in eastern Europe and a greater presence in the Balkans. In the British Isles it is almost absent from Ireland, further east in Scotland and also present in Wales. The simulated range for the OSU 2 x CO_2 climatic scenario (Fig.4.6c) shows a complete absence from the British Isles, and apart from the Alps, it is only present in Fennoscandia and Russia. In the North Atlantic region it is in Iceland, Jan Mayen and Bear Island. The simulation for the UKMO 2 x CO_2 climatic scenario (Fig.4.6d) shows a further northeastwards drift with it now in Svalbard. On the mainland of Europe it occurs in the north of Fennoscandia, the north of Russia, the Urals and the Alps.

4.2.4 *Hymenophyllum tunbrigense*: The response surface (Fig.4.7) shows its occurrences to be limited to areas where the MTCO is between 0°C and 6°C, with GDD5 <*ca* 2600 day degrees. There is little presence when the AET/PET is <0.85, showing its intolerance of dry conditions (see 3.1.4). The isolated occurrence at AET/PET 0.80 is related to its presence in the Azores and may reflect the difficulty in estimating the climate of these mountainous Atlantic islands.

The present simulation at a threshold probability of 0.30 (Fig.4.8b), when compared with the AFE distribution (Fig.4.8a) (Jalas & Suominen, 1972), shows an almost complete absence from the mainland of Europe, it is present only in France. In the British Isles more occurrences are simulated in Ireland but none in the southeast of England. The simulated range for the OSU 2 x CO_2 climatic scenario (Fig.4.8c) shows it to have moved northeastwards. It is no longer in the Azores but now on the west coast of the Iberian Peninsula, in peninsular Italy, the Balkans, southern Iceland and western Norway. In the British Isles there has been movement from the south to the north, reaching the Hebrides, Orkney and Shetland. The UKMO 2 x CO_2 climatic scenario (Fig.4.8d) shows a complete absence in the British Isles, with a greater presence in Iceland and Fennoscandia. It has spread further east in the Iberian Peninsula and is now on the west coast of France and also in Corsica.

4.2.5 *Hymenophyllum wilsonii*: The response surface (Fig.4.9) has almost no occurrence at AET/PET values <0.93, indicating an inability to withstand dry conditions(see 3.1.5). The species is limited by values of MTCO <-4°C and occurs between GDD5 values of *ca* 600 and *ca* 2400 day degrees. The exceptional occurrences are in the Azores and may reflect the poor estimation of the climate of these isolated Atlantic islands.

The present simulation at a threshold probability of 0.40 (Fig.4.10b) is well matched with the AFE distribution (Fig.4.10a) (Jalas & Suominen, 1972). The main discrepancy is a tendency for the simulated eastern limit in the British Isles to lie too far east. The simulated range for the OSU 2 x CO_2 climatic scenario (Fig.4.10c) shows a northward displacement, with occurrences simulated in Iceland and northern Norway. The southern limit in mainland Europe shows a northward shift, while the species is no longer in the Azores, although now simulated in the far north of the Iberian Peninsula. The UKMO 2 x CO_2 scenario (Fig.4.10d) shows both a greater northward displacement and a shift from the coastal fringe of Fennoscandia into the mountains of the interior. No occurrences are simulated in the British Isles.

4.2.6 *Dryopteris abbreviata*: The response surface (Fig.4.11) shows it to be limited by values of MTCO between -6°C and 7°C and to occur in a range of GDD5 values from *ca* 400 to *ca* 3200 day degrees. There is still a high probability of occurrence at AET/PET 0.82.

The present simulation at a threshold probability of 0.20 (Fig.4.12b) shows a marked limitation to western Europe; when matched with the AFE distribution (Fig.4.12a) (Jalas & Suominen, 1972) there is increased presence in the British Isles and Iceland. The OSU 2 x CO_2 scenario (Fig.4.12c) shows a general tendency for its range to move north and east; it is no longer in the Iberian Peninsula. In the British Isles it is on the south coast, and greatly reduced in the north of England and Scotland. It is present in southern Fennoscandia. The UKMO 2 x CO_2 scenario (Fig.4.12d) shows the drift has been further north, now reaching northern Fennoscandia and Svalbard; there are also two isolated occurrences in the Alps, and in the British Isles it is simulated only on Shetland.

4.2.7 *Polystichum lonchitis*: The response surface (Fig.4.13) shows this species to be limited by a MTCO <6°C, and GDD5 values <*ca* 3800 day degrees. The limiting AET/PET value is <0.50.

The simulation for present climate was made with a threshold probability of 0.30 (Fig.4.14b); it shows a more easterly and northern distribution in the British Isles than the AFE distribution (Fig.4.14a) (Jalas & Suominen, 1972). On the mainland of Europe there also are more simulated occurrences in the south of Fennoscandia and the north of the southwestern former USSR. No occurrences are simulated in the Urals, but more in Iceland than are observed. The OSU 2 x CO_2 scenario (Fig.4.14c) shows a drift north and east; a complete absence from the Iberian Peninsula, in the British Isles occurrences only in Scotland, and occurrences on the North Atlantic Islands and Svalbard. The UKMO 2 x CO_2 scenario (Fig.4.14d) shows a further northward and eastward trend, no longer are any occurrences simulated in the British Isles. In southern Europe it is limited to the Alps, the Pyrenees and the Balkans, in northern Europe it is still in Fennoscandia, Russia, and the North Atlantic.

4.2.8 *Thalictrum alpinum*: The response surface (Fig.4.15) shows an intolerance of dry conditions as there is virtually no occurrence at an AET/PET <0.90. It is limited to an MTCO value <6°C, and GDD5 value <*ca* 3000 day degrees.

The present simulation at a threshold probability of 0.30 (Fig.4.16b), when compared with the AFE distribution (Fig.4.16a) (Jalas & Suominen, 1989), shows similarity in the British Isles and northern Europe with additional occurrence in Svalbard. There are notable absences in southern Spain, the Pyrenees and the Balkans. The OSU 2 x CO_2 scenario (Fig.4.16c) shows a northward trend, except in the British Isles where it is absent from Scotland but is now present in the south and east of England. It occurs in western mainland Europe and the Alps' but is restricted to the west and north of Fennoscandia, the north coast of Russia, Jan Mayen and Bear Island. The UKMO 2 x CO_2 scenario (Fig.4.16d) shows a further trend north; it is absent from the British Isles, being mainly concentrated in northern Fennoscandia, Russia and the North Atlantic Islands.

4.2.9 *Subularia aquatica*: The response surface (Fig.4.17) shows the main limit of this species to be MTCO values between 6°C and -15°C with GDD5 between *ca* 200 and *ca* 1800 day degrees. The AET/PET values show little occurrence at <0.80.

The normal simulation at a threshold probability of 0.20 (Fig.4.18b) compares well with the NAFE distribution (Fig.4.18a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965) although it shows more occurrences in the

British Isles, Fennoscandia, and the Alps. These differences are probably due to the limitations of the bioclimate data, this is an aquatic species, growing in the shallow water of base-poor pools and lakes (see 3.2.2). The OSU 2 x CO_2 scenario (Fig.4.18c) shows a movement northwards, in the British Isles only occurring in Scotland. It is in western Fennoscandia, northern Russia and isolated places in the Alps. There is an increase in Iceland and it now occurs on Jan Mayen and Bear Island. The UKMO 2 x CO_2 scenario (Fig.4.18d) shows a further movement northward, absence in the British Isles, and occurrences mainly in the north of Fennoscandia and Russia as well as the North Atlantic Islands.

4.2.10 ***Draba incana***: The response surface (Fig.4.19) shows that the distribution is limited to MTCO values between 4°C and -14°C with GDD5 values <*ca* 2400 day degrees, and AET/PET values >0.75.

The simulation for the present climate at a threshold probability of 0.30 (Fig.4.20b) shows some differences from the NAFE distribution (Fig.4.20a) (Hultén, 1950, 1958; Perring & Walters, 1990). The main discrepancies are an increase in Scotland, and a reduction in the Pyrenees. The OSU 2 x CO_2 scenario (Fig.4.20c) shows it to have a moved north, being absent in the British Isles and with a reduced presence in the Alps. The UKMO 2 x CO_2 scenario (Fig.4.20d) shows a further shift north and eastward, it is now on Jan Mayen, Bear Island and Svalbard.

4.2.11 ***Silene acaulis***: The response surface (Fig.4.21) shows that the distribution is concentrated in regions where GDD5 values are <*ca* 1500 day degrees and MTCO values are <5°C. There is a reduction in occurrence when the AET/PET values are <0.95.

The simulation for the present distribution (Fig.4.22b) is well matched to the AFE distribution (Jalas & Suominen, 1986) at a threshold probability of 0.25. (Fig.4.22a.) The most striking discrepancies relate to areas of occurrence in the north of Spain and the Pyrenees, the Carpathians, peninsular Italy and the Alps, in all of which there are fewer occurrences simulated then observed. This is most probably due to the use of climate values estimated for mean elevation. The OSU 2 x CO_2 scenario (Fig.4.22c) appears to be similar to that simulated from present climate. The occurrences simulated for the north of Fennoscandia, Iceland, Jan Mayen, Bear Island and Svalbard dominate the pattern. The main differences are the disappearance from Scotland and reduction in number of simulated occurrences in central and southern Europe. The UKMO 2 x CO_2 scenario (Fig.4.22d) shows further reduction in central Europe and decline in Iceland and Fennoscandia.

4.2.12 *Geranium sylvaticum*: The response surface (Fig.4.23) shows it to grow at AET/PET values >0.48 with a widespread pattern of GDD5 values from *ca* 200 to *ca* 4400 day degrees and MTCO values <8°C. High MTCO values occur with the increased GDD5 values.

The present climate simulation with a threshold probability of 0.50 (Fig.4.24b) compares well with the NAFE distribution (Fig.4.24a) (Hultén, 1950; Meusel *et al.*, 1978; Perring & Walters, 1990) with the exception of the Iberian Peninsula and peninsular Italy. The OSU 2 x CO_2 scenario (Fig.4.24c) gives more abundant simulated occurrences in Ireland, an extension further south in England and a reduced range in Scotland. The pattern in northern Europe is similar to the present except for southern Fennoscandia where it is reduced in frequency of occurrence it now occurs on Jan Mayen and Bear Island. In southern Europe there is a northward trend except in the Iberian Peninsula. The UKMO 2 x CO_2 scenario (Fig.4.24d) shows it has moved north and east, occurring in Scotland, the Alps, the Balkans and eastern Spain. It is concentrated in northern Europe, principally in northeastern Fennoscandia and Russia. It is simulated as occurring on Svalbard, Jan Mayen and Bear Island, but much reduced in Iceland.

4.2.13 *Vicia orobus*: The response surface (Fig.4.25) shows it to have a climatic space with GDD5 values between *ca* 1000 and *ca* 3800 day degrees, MTCO values between 9°C and -4°C and AET/PET >0.75.

The principal difference between the simulation for the present climate, with a threshold probability of 0.20 (Fig.4.26b), when compared with the NAFE distribution (Fig.4.26a) (Hultén, 1950; Meusel *et al.*, 1965; Perring & Walters, 1990) occurs in the British Isles with an increase in the number of occurrences in Scotland. The OSU 2 x CO_2 scenario (Fig.26c) shows a drift westward and north; in the British Isles it is concentrated on the west coast of the mainland and in the southwest of Ireland. On the continent it is mainly present in the western Mainland and southern Fennoscandia, the Alpine region and the Balkans. The UKMO 2 x CO_2 scenario (Fig.4.26d) shows that in the British Isles it is only in Scotland. On the continent there are two distinct areas simulated; a scattering in Fennoscandia and also a limited spread from the south east of Spain through the Alpine region to the Balkans.

4.2.14 ***Rubus saxatilis***: The response surface (Fig 4.27) shows the main distribution to be limited by an MTCO value of <4°C, and GDD5 values between *ca* 200 and *ca* 2800 day degrees, and AET/PET values >0.30. The ability to grow at low AET/PET values is indicative of its occurrence in stony woods (see.3.2.7).

The simulation for present climate at a threshold probability of 0.30 (Fig.4.28b) corresponds well with the NAFE distribution (Fig.4.28a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965), the principal differences being that the simulation shows a greater distribution in northern Britain and in the central Iberian Peninsula; and occurrences in Svalbard. The OSU 2 x CO_2 scenario (Fig.4.28c) shows a marked shift south and west in the British Isles. On mainland Europe the general shift is to the north east, with the exception of the west of western mainland Europe. It is now present in the North Atlantic Islands. The UKMO 2 x CO_2 scenario (Fig.4.28d) shows it to be concentrated in Russia, northern Fennoscandia, the Alps, Carpathians and the mountainous region of the Balkans. In the British Isles it is only in north west Scotland. Its presence is reduced in Iceland, although it is simulated as occurring still on Bear Island and Svalbard.

4.2.15 ***Rubus chamaemorus***: The response surface (Fig.4.29) shows it to be limited at AET/PET <0.75, with MTCO values <4°C and GDD5 <*ca* 1600 day degrees.

The simulated map for present climate conditions at a threshold probability of 0.50 (Fig.4.30b) compares well with the NAFE distribution map (Fig.4.30a) (Hultén, 1950, 1970; Perring & Walters, 1990; Meusel *et al.*, 1965) with the exception of it being simulated as present in the Alps, Carpathians, the Balkans and Iceland. This may reflect limitation by a further non-climatic factor, or biogeographic or historical factors that have excluded the species from parts of its potential range. The absence from the mountains of central and southern Europe may reflect the combination of geology and topography that renders peatlands uncommon (see 3.2.8); the absence from Iceland more likely results from the geographic isolation of this island. In the OSU 2 x CO_2 scenario (Fig.4.30c) it is absent in the British Isles except for Scotland. On mainland Europe it occurs in the Alps, northern Fennoscandia, the north of Russia and Iceland. The UKMO 2 x CO_2 scenario (Fig.4.30d) shows it occurring in the Alps, the far north of Fennoscandia, Russia, the southeast of Iceland, eastern Svalbard and on Jan Mayen.

4.2.16 *Potentilla fruticosa*: The response surface (Fig.4.31) shows two distinct climatic regions. Its occurrence being limited to MTCO values between -6°C and +6°C and GDD5 between *ca* 1000 and *ca* 3200 day degrees. There is virtually no presence at AET/PET <0.75, supporting its preference for intermittently wet conditions (see 3.2.9).

The simulation for present climatic conditions at a threshold probability of 0.15 (Fig.4.32b) compares well with the NAFE distribution (Fig.4.32a), (Hultén, 1950, 1970; Perring & Walters, 1990; Meusel *et al.*, 1965), the only significant absence is in western Ireland. The OSU 2 x CO_2 scenario (Fig.4.32c) shows a movement eastward and northwards. In the British Isles it is simulated as occurring only in central Scotland. It occurs in the north of the western mainland of Europe and central southwestern former USSR. The UKMO 2 x CO_2 scenario (Fig.4.32d) virtually limits its distribution to northern Fennoscandia.

4.2.17 *Potentilla crantzii*: The response surface (Fig.4.33) shows that growth is limited to MTCO values above -16°C, with an upper limit of 6°C, and GDD5 ranges from *ca* 200 to *ca* 3000 day degrees. It still occurs when the AET/PET is 0.75. The main concentration occurs at lower temperatures where the AET/PET values are >0.80.

The simulated occurrences for present day climate at a threshold probability of 0.25 (Fig.4.34b) when compared with the NAFE distribution (Fig.4.34a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965), show some differences. It is absent from the west of the Iberian Peninsula, the Mediterranean Islands, and peninsular Italy. In the British Isles it occurs in north Wales and shows more occurrences in Scotland. On the mainland of Europe it occurs in the north of south western former USSR, and is further east in Fennoscandia. The OSU 2 x CO_2 scenario (Fig.4.34c) in general shows a northeastern movement. In the British Isles it is now virtually restricted to the southeast of England. On the mainland of Europe it is concentrated in central Europe, the Alps, northern southwestern former USSR, central and northern Russia and north Fennoscandia. It occurs on the North Atlantic Islands, but no longer in the south west of Iceland. The UKMO 2 x CO_2 scenario (Fig.4.34d) simulation shows it having disappeared from the British Isles. It is in the north of Fennoscandia, the north and east of European Russia and in the Alps, but greatly reduced in the Carpathians and the Balkans.

4.2.18 ***Dryas octopetala***: The response surface (Fig.4.35) shows the European distribution to extend down to an AET/PET of 0.75. It is limited to MTCO <5°C, and GDD5 <*ca* 2400 day degrees. At AET/PET <0.93 the MTCO values are between -6°C and zero, with GDD5 >*ca* 1400 day degrees. This confirms the existence of two distinct European ranges, one in the sub-arctic and the other in the temperate mountains.

The simulation for present day climate at a threshold probability of 0.15 (Fig.4.36b) shows some differences when compared with the NAFE distribution (Fig.4.36a) (Hultén, 1950, 1970; Perring & Walters, 1990; Meusel *et al.*, 1965). The principal differences are increased occurrences in the British Isles, and absence in the Pyrenees and peninsular Italy; this latter difference may be due to the fact that it grows in the high mountains of southern Europe whereas the bioclimatic data are for mean elevation. It is also absent from the east of European Russia. In the simulation for the OSU 2 x CO_2 scenario (Fig.4.36c) the British Isles shows only a limited number of occurrences in Scotland. On the mainland of Europe it has shifted north and east, occurring in the southwest of the former USSR, in the north of Russia and further east in Fennoscandia. It is also present in the North Atlantic Islands. In the UKMO 2 x CO_2 scenario (Fig.4.36d) it is essentially absent from southern Europe, with minimal distribution in the Alps and southern Russia. In northern Europe it occurs in the west and north of Fennoscandia and northern Russia. It also occurs in Svalbard and on Bear Island, but is reduced in Iceland.

4.2.19 *Alchemilla alpina*: The response surface (Fig.4.37) shows that this species is widespread in climatic space, still occurring at an AET/PET of 0.75; the MTCO limiting value is <7°C and GDD5 <*ca* 3800 day degrees. This is characteristic of its wide dispersal from sea-level to mountain tops.

The simulated map at a threshold probability of 0.25, (Fig.4.38b) compares well with the NAFE distribution (Fig.4.38a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965), the main discrepancies being the absence of simulated occurrences in Ireland, the east of the Iberian Peninsula and south western former USSR. The OSU 2 x CO_2 scenario (map 4.2.38c) shows a general move northwestwards. In the British Isles it now occurs in the south of England and to the west in Scotland, Wales and Ireland. It is present in western mainland Europe, northern central Europe and the far north of southwestern former USSR. It occurs in the north and west of Fennoscandia, and in the North Atlantic Islands. The UKMO 2 x CO_2 scenario (Fig.4.38d) shows it has spread further north. In southern Europe it is restricted to the Alps, eastern Spain and the Balkans. In the British Isles it is present only in Scotland and Shetland. In Fennoscandia it is mainly in the north and the southwest. It occurs in the far north of European Russia, Bear Island and Svalbard, with a reduced amount in Iceland.

4.2.20 *Rhodiola rosea*: The response surface (Fig.4.39) shows a widespread distribution wherever the AET/PET is >0.75. The MTCO values are between -16°C and 4°C, the GDD5 values <*ca* 2400 day degrees. With an AET/PET <0.93 it occurs with GDD5 between *ca* 1800 and *ca* 2200 day degrees, and MTCO between -5°C and 2°C.

The simulation for present climatic conditions at a threshold probability of 0.25 (Fig.4.40b) shows some differences from the NAFE distribution (Fig.4.40a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965). The simulation for the British Isles shows it further east in Scotland and the north of England, and occurring in the north of Ireland. On the European mainland there are fewer occurrences in the Iberian Peninsula, the Balkans and central Europe. In Fennoscandia it is simulated occurring further south and also in the northwest. The OSU 2 x CO_2 scenario (Fig.4.40c) shows a northward movement; it is simulated occurring in central Scotland, western mainland Europe, central Europe and the Alps. It has extended its range into the northeast of Fennoscandia, and the North Atlantic Islands. In the UKMO 2 x CO_2 scenario (Fig.4.40d) it has disappeared in the British Isles, and is reduced in the Alps. It is still occurring in the west and north of Fennoscandia, the north of Russia and in the North Atlantic Islands, although reduced in Iceland.

4.2.21 *Sedum villosum*: The response surface (Fig.4.41) shows a wide spread in its climatic space, although with virtually no presence at AET/PET <0.38. The GDD5 values range from *ca* 200 to *ca* 4400 day degrees with MTCO between -11°C and 10°C. At AET/PET 1.0 it occurs at lower MTCO values, <4°C, and the GDD5 values are <*ca* 3000 day degrees. At the lower range of AET/PET <0.62 the MTCO ranges from 4° to 10°C and the GDD5 values rise to over 4000 day degrees. These figures shows that it ranges from moist sites in the cool north to drier areas in the warmer south.

The distribution map simulated for present climatic conditions at a threshold probability of 0.35 (Fig.4.42b) shows a wider spread in southern Europe than the NAFE distribution (Fig.4.42a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965). It is simulated to occur in eastern Spain, peninsular Italy, the Mediterranean Islands and the Balkans. In Fennoscandia it occurs in the southwest, but not in the far north. In the British Isles its presence is reduced to the north of England. In the OSU 2 x CO_2 scenario (Fig.4.42 21c) it has moved west and south in the British Isles, being restricted to the west coast of Scotland, southern Ireland, Wales and England. On the mainland of Europe it has spread east in the Iberian Peninsula, into the southwest of the former USSR, the Balkans and peninsular Italy. In Fennoscandia it is mainly in the south, and up the western side to the far north east. In the North Atlantic region it is occurring on Jan Mayen and Bear Island; in Iceland it is reduced. The UKMO 2 x CO_2 scenario (Fig.4.42d) shows that in the British Isles it is now restricted to Scotland. On the mainland of Europe it has moved north and east, the main area being in Russia and Fennoscandia, where it is in the east and along the Norwegian coastline, it occurs in the Alps, Carpathians and the Balkans. There are scattered localities in western mainland Europe, central Europe and Spain. In the North Atlantic region it occurs in the west of Iceland and also on Svalbard and Bear Island.

4.2.22 *Saxifraga nivalis*: The response surface (Fig.4.43) shows that this species does not grows in an environment with an AET/PET <0.93, indicating the need for moist conditions (see 3.2.15). The MTCO value limits the growth to <4°C and the GDD5 value is <*ca* 1600 day degrees.

The simulated distribution map for the present climate with a threshold probability of 0.25 (Fig.4.44b) shows a good match to the NAFE distribution (Fig.4.44a) (Hultén, 1950, 1970; Perring & Walters, 1990; Meusel *et al.*, 1965) in northern Europe. However the simulation shows the presence of the species in the Alps; this probably reflects a potential area of distribution for the species from which it has been excluded by biogeographic barriers and/or environmental history. The NAFE distribution does, however, show isolated presences in western mainland and central Europe. In the British Isles the simulation shows it only occurring in central Scotland. The OSU 2 x CO_2 scenario (Fig.4.44c) gives a much reduced distribution, being confined almost entirely to the North Atlantic Islands. In the simulation for the UKMO 2 x CO_2 scenario (Fig.4.44d) it is only in the northwest of Fennoscandia, on Bear Island and Svalbard.

4.2.23 *Saxifraga stellaris*: The response surface (Fig.4.45) shows that the species requires a damp environment (see 3.2.16) with limiting values of AET/PET <0.93, MTCO between -16°C and 4°C and GDD5 <*ca* 1800 day degrees.

The simulated map for present climate at a threshold probability 0.35 (Fig.4.46b), when compared with the NAFE distribution (Fig.4.46a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965), shows similarity in northern Europe. In the British Isles, fewer occurrences are simulated in Scotland, England and Wales, whereas in Ireland it is virtually absent. In southern Europe the simulation generates occurrences in the Alps. Once again the absence from this region probably reflects biogeographic and/or historic factors. The OSU 2 x CO_2 scenario (Fig.4.46c) simulates the distribution moving north and west; it is no longer present in the British Isles, and it is reduced in the Alps. The main concentration now is in the northwest of Fennoscandia and on the north coast of Russia. It also is simulated to occur in Svalbard, on Jan Mayen, Bear Island and Iceland. The UKMO 2 x CO_2 scenario (Fig.4.46d) shows a further shift north, occurrences being restricted to northern Fennoscandia with isolated sites in the southwest. It also occurs on the north coast of Russia, Bear Island, Svalbard and Iceland.

4.2.24 *Saxifraga aizoides*: The response surface (Fig.4.47) shows that MTCO values of between -15°C and 4°C limit growth, with GDD5 values <*ca* 2800 day degrees. The main distribution has an AET/PET >0.93. At AET/PET values of 0.93 to 0.75 the climatic space is more restricted; the GDD5 values are between *ca* 1800 and *ca* 2800 day degrees and MTCO >-6°C.

The distribution map for present day climate at a probability threshold of 0.25 (Fig.4.48b) compares well with the NAFE distribution (Fig.4.48a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965), the main differences being in the British Isles where the simulation shows a wider distribution in Scotland and northern England, and occurrences in north Wales. On the mainland of Europe it is absent in northern Russia and is reduced in peninsular Italy. In Iceland there is an increased distribution, extending further west. The OSU 2 x CO_2 scenario, (Fig.4.48c) shows that in the British Isles it is only in an isolated place in Scotland. There is a marked drift east on mainland Europe, the range now being largely restricted to central Europe, the Balkans, southwestern former USSR, the Alps and the south and north of Russia. In Fennoscandia it has spread in the northeast; in Iceland and Svalbard there is an easterly trend. The UKMO 2 x CO_2 scenario (Fig.4.48d) shows a further drift northeast, it is absent in the British Isles. In mainland Europe the greatest concentration is in the Urals, the Alps, the Balkans and Carpathians. In northern Europe it is in the north of Russia and Fennoscandia, in southern Iceland and the east of Svalbard.

4.2.25 *Saxifraga oppositifolia*: The response surface (Fig.4.49) shows that MTCO between -16°C and 6°C is limiting, with GDD5 values from zero to <*ca* 3600, the higher values at AET/PET <0.90. The greatest concentration at lower temperatures occur at AET/PET >0.93. AET/PET is not limiting at 0.75.

The simulated distribution map at threshold probability 0.30 (Fig.4.50b) compares well with the NAFE distribution (Fig.50a) (Hultén, 1950, 1970; Perring & Walters, 1990; Meusel *et al.*, 1965) for northern Europe. In the British Isles the simulation tends to have an eastern distribution, nothing occurring in Ireland. In southern Europe, it is reduced in the Iberian Peninsula and peninsular Italy. The OSU 2 x CO_2 scenario (Fig.4.50c) has a distribution in which there has been a northeastwards trend. In the British Isles the distribution is now in the south and along the west coast. There is a considerable distribution in the west of the western mainland of Europe, but very little in the Iberian Peninsula and peninsular Italy. In the Alps the distribution is reduced, but increased in southern Russia. In Fennoscandia the spread is north and east, and isolated sites occur on the north coast of Russia. In Svalbard it has increased, but in Iceland it is reduced. The

UKMO 2 x CO_2 scenario (Fig.4.50d) shows a further northeastwards drift, in the British Isles it is only occurring in the northwest of Scotland. On the mainland of Europe it is reduced in Iberia and the Alps, and is absent in the western mainland. There is a concentration in the centre and on the north coast of European Russia. In Fennoscandia the main distribution is in the north, with some in the south and west of Norway, in Iceland it has reduced further.

4.2.26 *Epilobium anagallidifolium*: The response surface (Fig.4.51) shows the MTCO value to limit occurrence to between -16°C and 6°C with GDD5 <*ca* 3000 day degrees. The AET/PET does not limit growth at 0.75, the lower temperatures occur with higher AET/PET values, the range of occurrence reducing at AET/PET values <0.93.

The simulated distribution at a threshold probability of 0.20 (Fig.4.52b) compares well with the NAFE distribution (Fig.4.52a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1978), the main discrepancy being the absences from northern England and southern Scotland and central Europe. The OSU 2 x CO_2 scenario (Fig.4.52c) shows a northeastwards shift. In the British Isles the distribution is now mainly in the south and on west coasts. There is an increase in western mainland and central Europe, the Balkans, central and northern European Russia and southwestern former USSR. In Fennoscandia the distribution has spread east and it now occurs in Svalbard. The UKMO 2 x CO_2 scenario (Fig.4.52d) shows a further northward movement; in the British Isles occurrences are simulated only in northern Scotland. On mainland Europe the main concentration is in northern Russia, with limited occurrences in the Alpine region. In Fennoscandia the distribution is mainly on the western and northern coast. On Svalbard it is in the northeast, and in the south of Iceland.

4.2.27 *Epilobium alsinifolium*: The response surface (Fig.4.53) shows that it is limited to MTCO values between -16°C and 6°C with GDD5 <*ca* 3000 day degrees. The plant still occurs at AET/PET 0.75 but at the higher end of the temperature range. The greatest concentration occurring at AET/PET >0.85.

The simulated distribution map for present climate at a threshold probability 0.25 (Fig.4.54b) has a good agreement for southern Europe with the NAFE distribution (Fig.4.54a) (Hultén, 1950; Perring & Walters, 1990; Meusel *et al.*, 1978). In the British Isles the simulation shows fewer occurrences in northern England, reduced presence in Scotland and absence in Ireland, and a limit that lies further east in Wales. There also are more occurrences in the simulated map in Fennoscandia and Iceland. The OSU 2 x CO_2 scenario (Fig.4.54c) shows a northeastwards drift from the south of Europe. In the British Isles it is mainly in the south of England and on the west coast. In western mainland Europe it is concentrated in the west, in central Europe there has been a northward movement and it has become concentrated in central and northern European Russia. In Fennoscandia it is in the west, the south and the northwest. It is in Svalbard and on Bear Island. In the UKMO 2 x CO_2 scenario (Fig.4.54d) it has shifted further north, in the British Isles occurring only in northern Scotland, and in southern Europe only in the Alpine region. In northern Europe it is restricted to scattered sites in Fennoscandia and in the centre and north of Russia. It is still simulated as occurring in Svalbard, Bear Island and southern Iceland.

4.2.28 *Meum athamanticum*: The response surface (Fig.4.55) shows that it is limited at AET/PET values <0.60. The MTCO limits growth between -8°C and 8°C, the GDD5 values are between *ca* 600 and *ca* 3600 day degrees. The greatest probability of it occurring is at AET/PET >0.75, with MTCO values between -1°C and +4°C with GDD5 values between *ca* 2200 and *ca* 3000 day degrees.

The simulated distribution map for the present climate at a threshold probability 0.20 (Fig.4.56b) compares well with the NAFE distribution (Fig.4.56a) (Hultén, 1950; Perring & Walters, 1990; Meusel *et al.*, 1978). The principal differences are in the British Isles where it tends to be simulated occurring further east in England and north in Scotland. In Fennoscandia and on the Mediterranean Islands more occurrences are simulated than are observed. The OSU 2 x CO_2 scenario (Fig.4.56c) shows an eastward movement with a northern trend. In the

British Isles it only occurs in central England. The main concentration is in central Europe extending into the Alpine region, the Balkans and the north of southwestern former USSR. In Fennoscandia it is occurring in the south and the far north and east. There are isolated occurrences in western mainland Europe, the Iberian Peninsula and peninsular Italy. The UKMO 2 x CO_2 scenario (Fig.4.56d) leads to a simulated distribution that is concentrated in the northeast of Fennoscandia, northern Russia and the Alps.

4.2.29 *Polygonum viviparum*: The response surface (Fig.4.57) shows that it is limited at AET/PET values >0.75, moist conditions being required for survival (see 3.22). The MTCO value limits it to <4°C, and GDD5 <*ca* 2600 day degrees.

The simulated map for present climate with a threshold probability 0.35 (Fig.4.58b) compares closely with the AFE distribution (Fig.4.58a) (Jalas & Suominen, 1979). In the British Isles the simulation in southern Scotland tends to be too far east, in Ireland it is shown in the north but absent in the south west. On the European mainland it is absent in the Iberian Peninsula, but there is an increase in northern Russia and eastern Fennoscandia. The OSU 2 x CO_2 scenario (Fig.4.58c) shows a shift northwards. In the British Isles it is only in central Scotland. The main concentration is in northern and western Fennoscandia, northern Russia and the Alpine region with scattered sites in central and western Europe. In the North Atlantic region it is present on Jan Mayen, Bear Island and Svalbard. The UKMO 2 x CO_2 scenario (Fig.4.58d) shows a further northward drift, occurrences now being restricted to the Alps, northern Fennoscandia, Russia, the North Atlantic Islands and Iceland.

4.2.30 *Oxyria digyna*: The response surface (Fig.4.59) has a reduced distribution at AET/PET <0.80 showing the need for moisture. The MTCO value limits growth at 5°C with GDD5 values <*ca* 2600 day degrees. At AET/PET <0.90 it occurs at GDD5 values between *ca* 1600 and *ca* 2600 day degrees.

The distribution map simulated for present climate with threshold probability 0.25 (Fig.4.60b) corresponds closely with the AFE distribution

(Fig.4.60a) (Jalas & Suominen, 1979). The main area of discrepancy is in the British Isles; in northern England it spreads further east and south, in Ireland the spread is further east and north, it also shows more occurrences in Orkney and Shetland. On the mainland of Europe the greatest difference is its virtual absence in the Balkans. The OSU 2 x CO_2 scenario (Fig.4.60c) shows that in the British Isles it occurs only in central Scotland. In Europe it occurs in the Alpine region, the north of Russia, and the west and north of Fennoscandia. It is throughout the North Atlantic Islands. In the UKMO 2 x CO_2 scenario (Fig.4.60d) it is now absent in the British Isles, reduced in the Alps, southwest Fennoscandia and Iceland, but persisting on Svalbard.

4.2.31 ***Salix phylicifolia***: The response surface (Fig.4.61) shows no occurrences at AET/PET <0.75 indicating the need for moist conditions. The MTCO limits occurrence to <4°C and the GDD5 values <*ca* 1800 day degrees.

The distribution map for present climate at threshold probability 0.35 (Fig.4.62b) is compatible with the AFE distribution (Fig.4.62a) (Jalas & Suominen, 1976), for northern Europe. The principal difference is in southern Europe where it is simulated occurring in the Alps, Carpathians and the Balkans. In the British Isles it is simulated to be occurring in Wales and the north of Ireland. The OSU 2 x CO_2 scenario (Fig.4.62c) shows it has moved northward, persisting only in central Scotland, the Alps, northern Russia and the north west of Fennoscandia. It is present on Jan Mayen, Bear Island and the west of Svalbard. In the UKMO 2 x CO_2 scenario (Fig.4.62d) it has shifted further north and only occurs in the far north of mainland Europe and the North Atlantic Islands.

4.2.32 ***Salix herbacea***: The response surface (Fig.4.63) AET/PET limits growth at >0.9, indicating the inability of the species to grow in all but moist conditions. The MTCO limits at <5°C and the GDD5 values <*ca* 2400 day degrees.

The simulated distribution for present climatic values with threshold probability 0.30 (Fig.4.64b) compares well with the AFE distribution (Fig.4.64a) (Jalas & Suominen, 1976). The greatest differences are in the British Isles where the limit is simulated too far east, and in southern Europe where the range is reduced. The OSU 2 x CO_2 scenario (Fig.4.64c) has it almost entirely restricted to the far north of Europe, western Fennoscandia and the North Atlantic Islands. In the British Isles it is in central Scotland, and in southern Europe only in the Alps. In the UKMO 2 x CO_2 scenario (Fig.4.64d) it no longer is simulated as occurring in the British Isles; there also are reductions of range in the Alps, western Fennoscandia and Iceland.

4.2.33 *Utricularia intermedia*: The response surface (Fig.4.65) shows the species limited to areas where MTCO is <5°C and GDD5 values lie between *ca* 200 and *ca* 2200 day degrees. This plant grows in shallow pools and ditches (see 3.2.26); it occurs at AET/PET >0.65. At the lowest AET/PET values the MTCO is <-8°C.

The simulated distribution for present climate at threshold probability 0.25 (Fig.4.66b) has a good match with NAFE distribution (Fig.4.66a) (Hultén, 1950, 1970; Perring & Walters, 1990; Meusel *et al.*, 1978) in the north east of Europe. In the British Isles the simulation shows a complete absence from southern England and Ireland. In Europe the simulation shows extra occurrences in central Spain, peninsular Italy, western mainland and central Europe, the Alpine region, the Balkans and eastern Russia. The marked differences between this simulation and the actual distribution most probably are due to ecological factors that are not accounted for by the climatic data. The OSU 2 x CO_2 scenario (Fig.4.66c) shows it to be absent in the British Isles and reduced in southern Europe. Its main occurrence now is in Fennoscandia, excluding the extreme south, northern Russia and Iceland. In the UKMO 2 x CO_2 scenario, (Fig.4.66d) it has moved further east and is now mainly in Russia and Fennoscandia, although also still in the Alpine region and eastern Iceland.

4.2.34 *Galium boreale*: The response surface (Fig.4.67) shows that MTCO >6°C limits growth; occurrences also is only where GDD5 values are <*ca* 3100 day degrees. The AET/PET still permits growth at 0.25, this species surviving in dry conditions.

The simulated map for present climate at a threshold probability of 0.50 (Fig.4.68b) has variations at the distribution extremes when compared with the NAFE distribution (Fig.4.68a) (Hultén, 1950, 1958; Meusel *et al.*, 1992; Perring & Walters, 1990). In the British Isles the simulation tends to extend too far to the east, with complete absence in Ireland. On the mainland of Europe no occurrences are simulated in the Iberian Peninsula, whereas additional occurrences are simulated in peninsular Italy and to a greater extent in the Balkans. The simulation also generates occurrences in Svalbard. The OSU 2 x CO_2 scenario (Fig.4.68c) shows a northward shift, except in the south of England and Ireland and along the west coast of the British Isles. It now is present in western mainland Europe, the Alpine region, the Carpathians and the western Balkans. It occurs throughout the southwest of the former USSR, Russia and Fennoscandia except the extreme south, also on Jan Mayen and Bear Island. The UKMO 2 x CO_2 scenario (Fig.4.68d) shows it is further north and east; in the British Isles it now is simulated only in the north of Scotland. On the European mainland it occurs in the Alps, Pyrenees, Carpathians, the Balkans, throughout European Russia and the east and southwest of Fennoscandia; it also is simulated in the North Atlantic Islands.

4.2.35 *Cirsium helenioides*: The response surface (Fig.4.69) shows the need for moist conditions; the AET/PET limits occurrence to areas where it exceeds 0.60. It also is found only where MTCO <5°C; this limit is below zero when the AET/PET is <0.90. The GDD5 values are in the main <*ca* 2000 day degrees.

The simulated map for present climatic conditions at threshold probability 0.50 (Fig.4.70b) is compatible with the NAFE distribution (Fig.4.70a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1992) with the notable exception of Ireland and western mainland Europe. The OSU 2 x CO_2 scenario (Fig.4.70c) has a northern distribution. In the British Isles it extends further south and along the west coast. The main concentration occurs on the European mainland, in the north, and the Alps. It also occurs in Iceland. The UKMO 2 x CO_2 scenario (Fig.4.70d) shows it present only in Scotland, the Alps, the far north of mainland Europe, Svalbard, Jan Mayen and south east Iceland.

4.2.36 *Saussurea alpina*: The response surface (Fig.4.71) shows AET/PET <0.90 virtually limits occurrence, indicating the need for moist conditions. The MTCO limits at <5°C with GDD5 <*ca* 2400 day degrees.

The simulated map for present climate at a threshold probability 0.35 (Fig.4.72b) shows a northward shift when compared with the NAFE distribution (Fig.4.72a) (Hultén, 1950; Perring & Walters, 1990; Meusel *et al.*, 1992). In the British Isles the simulation shows complete absence in England, Wales and Ireland. In southern Europe the simulation restricts it to the Alpine region. The simulation also shows it to occur in Iceland. The OSU 2 x CO_2 scenario (Fig.4.72c) restricts it to the extreme north of mainland Europe, the Alps, Iceland and Svalbard. The UKMO 2 x CO_2 scenario (Fig.4.72d) has the distribution further reduced with no simulated occurrences in the Alps.

4.2.37 *Pseudorchis albida*: The response surface (Fig.4.73) shows AET/PET <0.60 to be limiting. The MTCO values are between -16°C and 5°C with GDD5 between *ca* 200 and *ca* 3200 day degrees. At AET/PET values <0.80 the lower limit of GDD5 values is *ca* 1800 day degrees and of MTCO -4°C.

The simulated distribution for present climate at a threshold probability 0.30 (Fig.4.74b) compares favourably with the NAFE distribution (Fig.4.74a) (Hultén, 1950, 1958; Perring & Walters, 1990; Meusel *et al.*, 1965). In the British Isles the simulation omits southern England and Ireland with an increase in Scotland. Omissions are also in western mainland Europe, the Carpathians and north Russia; it predicts its presence in Iceland however. The OSU 2 x CO_2 scenario (Fig.4.74c) has it moved north and east. In the British Isles it is only in the north of Scotland. In central Europe it has shifted further east and north to southwestern former USSR. In Fennoscandia it is widely dispersed in the north and west; it also is in the west of Iceland. In the UKMO 2 x CO_2 scenario (Fig.4.74d) it has drifted further east in northern Europe, whereas in the south it is restricted to the Alpine region and southwestern former USSR. In Iceland there are fewer simulated occurrences.

4.2.38 ***Sparganium angustifolium***: The response surface (Fig.4.75) shows only limited presence at AET/PET 0.80 with the MTCO limiting at values between -16°C and 5°C, the GDD5 limit is at <*ca* 2200 day degrees.

The simulation for present climate at threshold probability 0.35 (Fig.4.76b) for northern Europe compares well with the NAFE distribution (Fig.4.76a) (Hultén, 1950, 1958; Meusel *et al.*, 1965; Perring & Walters, 1990). In the British Isles it is absent in England and Ireland, but more occurrences are simulated in Wales and Scotland. It is absent in both the western mainland of Europe and the Iberian Peninsula. The simulated occurrences in the Alps, Carpathians and Balkans are too numerous; this is probably due to the climate data not being able to reflect the occurrence of the peaty lakes in which the plant grows (see 3.2.31). The OSU 2 x CO_2 scenario (Fig.4.76c) has the main concentration in the north of mainland Europe with some occurrences in the Alps, Iceland and Svalbard. The UKMO 2 x CO_2 scenario (Fig.4.76d) has a similar spread but with a reduced number of occurrences.

4.2.39 ***Carex magellanica***: The response surface (Fig.4.75) shows that MTCO limits growth to <4°C with GDD5 values <*ca* 2400 day degrees. AET/PET values of 0.75 are still permitting growth to occur.

The simulated distribution for present climate at threshold probability 0.40 (Fig.4.78b) corresponds well with the NAFE distribution (Fig.4.78a) (Hultén, 1950, 1962; Perring & Walters, 1990; Meusel *et al.*, 1965), the principal differences being simulated presences in the Balkans and the Iberian Peninsula. The OSU 2 x CO_2 scenario (Fig.4.78c) shows it moving northwards, in southern Europe occurring only in the Alps and elsewhere on the mainland only in the far north. It is simulated also to occur in Svalbard and eastern Iceland. The UKMO 2 x CO_2 scenario (Fig.4.78d) shows a further contraction with a shift to the east.

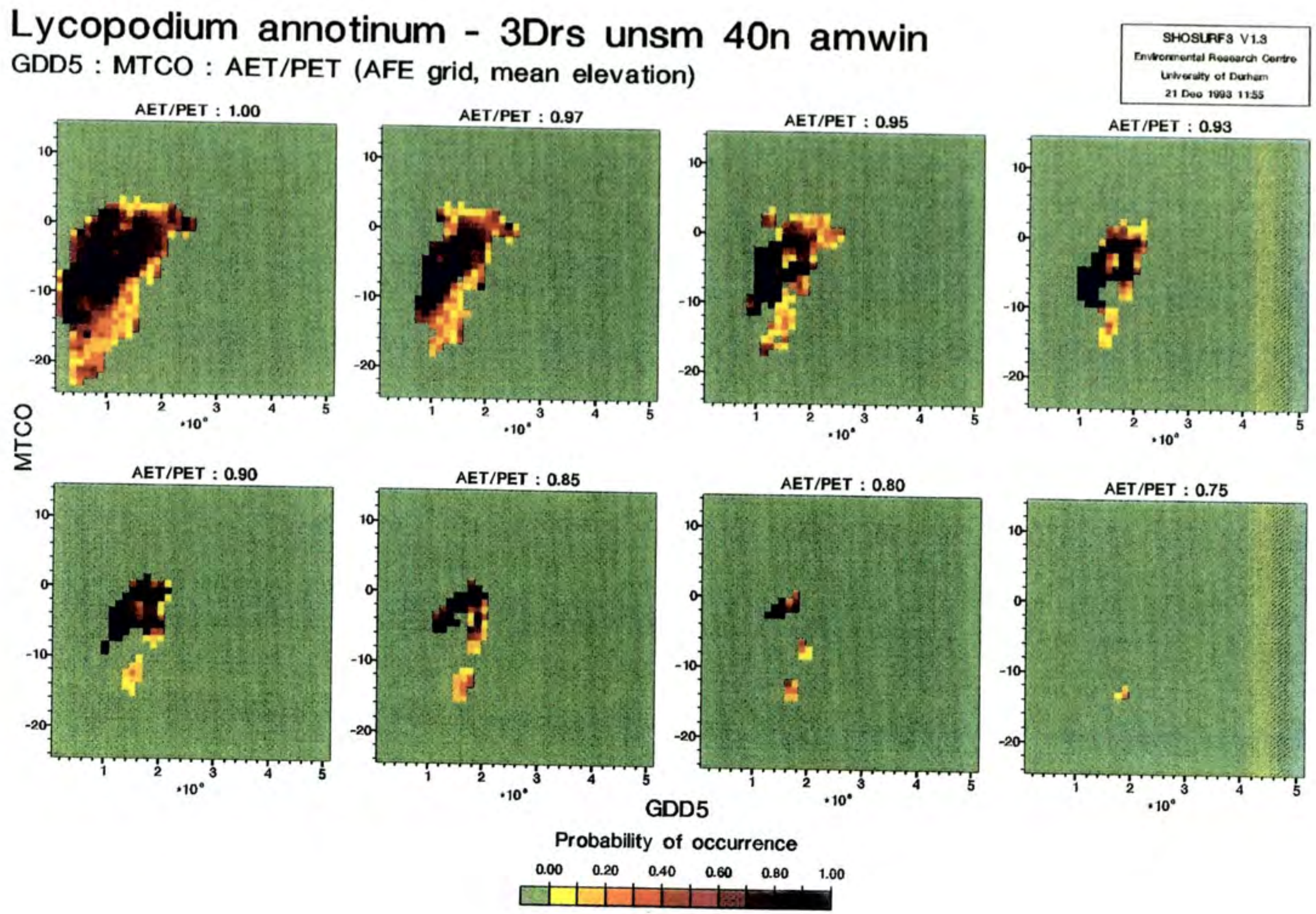
4.2.40 ***Carex bigelowii***: The response surface (Fig.4.79) shows occurrence is limited at AET/PET >0.93 with MTCO values limiting it to <6°C and GDD5 <*ca* 1800 day degrees.

The simulated distribution for present climate at threshold probability 0.25 (Fig.4.80b) matches well with the NAFE distribution (Fig.4.80a) (Hultén, 1950, 1962; Perring & Walters, 1990; Meusel *et al.*, 1965) for northern Europe. The main discrepancies in the simulation occur in the British Isles where it has a northeast bias, simulated occurrences being absent in England and southern Ireland. The simulation also shows it occurring in the Alps. The OSU 2 x CO_2 scenario (Fig.4.80c) shows it mainly in the far north of the European mainland and the North Atlantic region. There are some simulated occurrences in the Alps but nothing in the British Isles. The UKMO 2 x CO_2 scenario (Fig.4.80d) simulates occurrences only in the far north of the European mainland, Svalbard, Bear Island and Iceland.

4.4.41 ***Carex pauciflora***: The response surface (Fig.4.81) shows a limit at AET/PET <0.80. The MTCO values are between -18°C and 5°C with GDD5 values <*ca* 2400 day degrees.

The distribution for present climate at a threshold probability of 0.50 (Fig.4.82b) has notable absences in western European mainland and the British Isles when compared with the NAFE distribution (Fig.4.82a) (Hultén, 1950, 1962; Perring & Walters, 1990; Meusel *et al.*, 1965). In the British Isles no occurrences are simulated in southern Scotland, Ireland or northern England. The OSU 2 x CO_2 scenario (Fig.4.82c) shows a simulated distribution limited to the northern mainland of Europe, the Alps and Iceland. The UKMO 2 x CO_2 scenario (Fig.4.82d) has moved the distribution further north and east, with occurrences in the Alps, Svalbard, and Iceland.

Figure 4.1



Lycopodium annotinum - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
21 Dec 1993 11:55
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.2 ***Lycopodium annotinum***

a. AFE distribution

b. Normal simulation threshold probability 0.35

c. OSU simulation

d. UKMO simulation

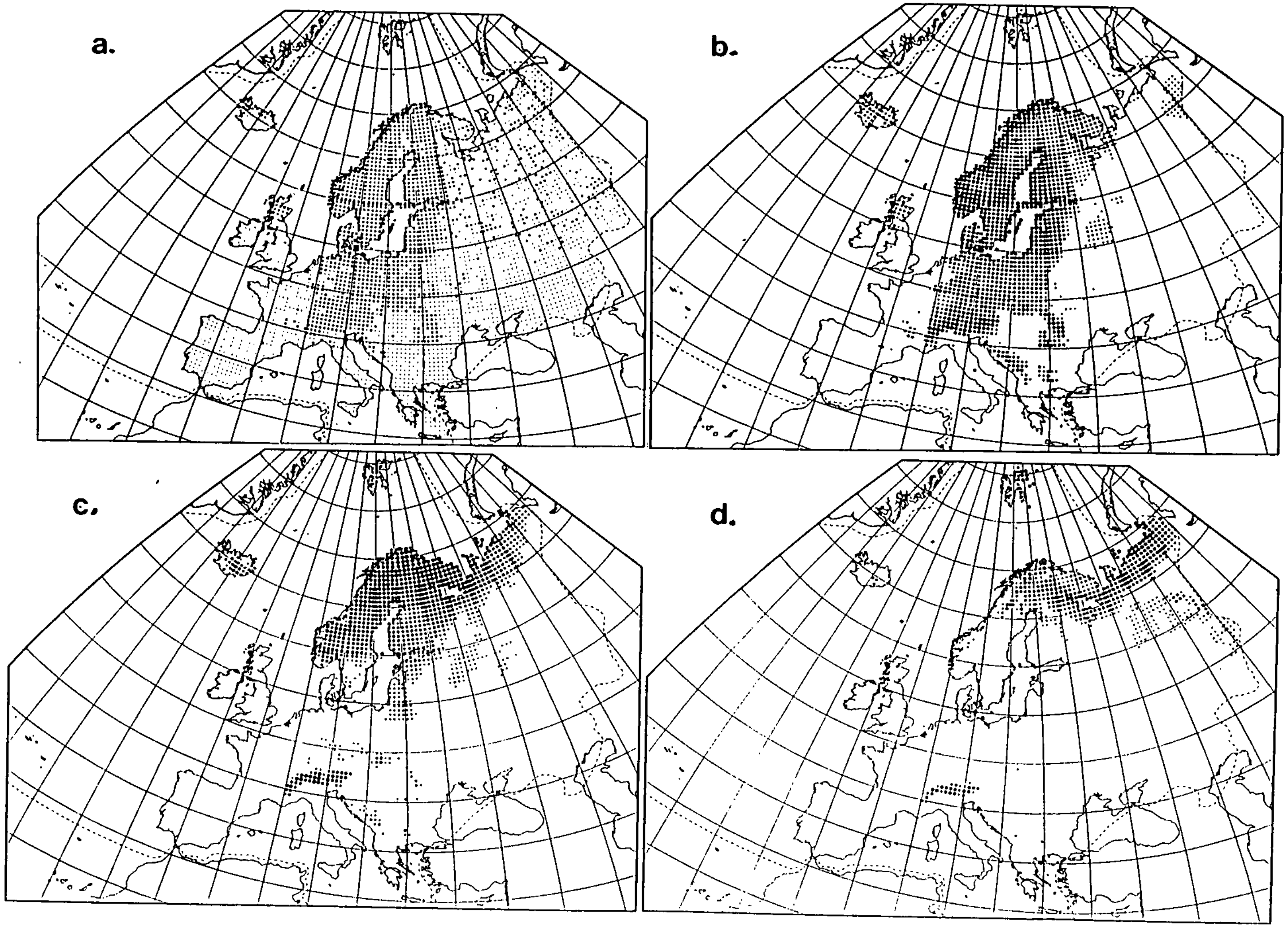
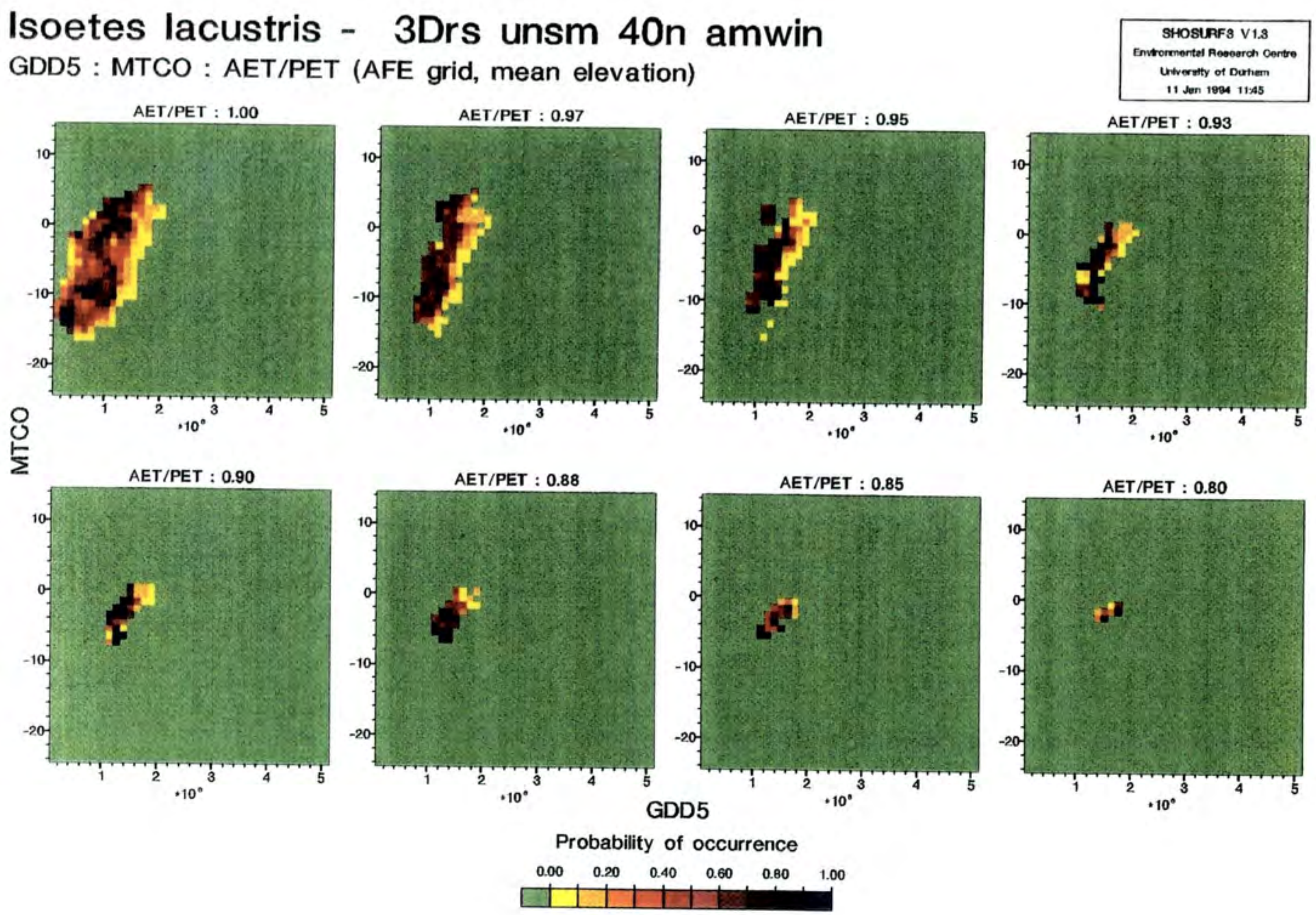

a.
b.
c.
d.

Figure 4.3



Isoetes lacustris - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
11 Jan 1994 11:45
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.88
AET/PET : 0.85
AET/PET : 0.80
10
0
-10
-20
1
2
3
4
5
*10°
MTCO
GDD5
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.4 ***Isoetes lacustris***

a. AFE distribution

b. Normal simulation threshold probability 0.40

c. OSU simulation

d. UKMO simulation

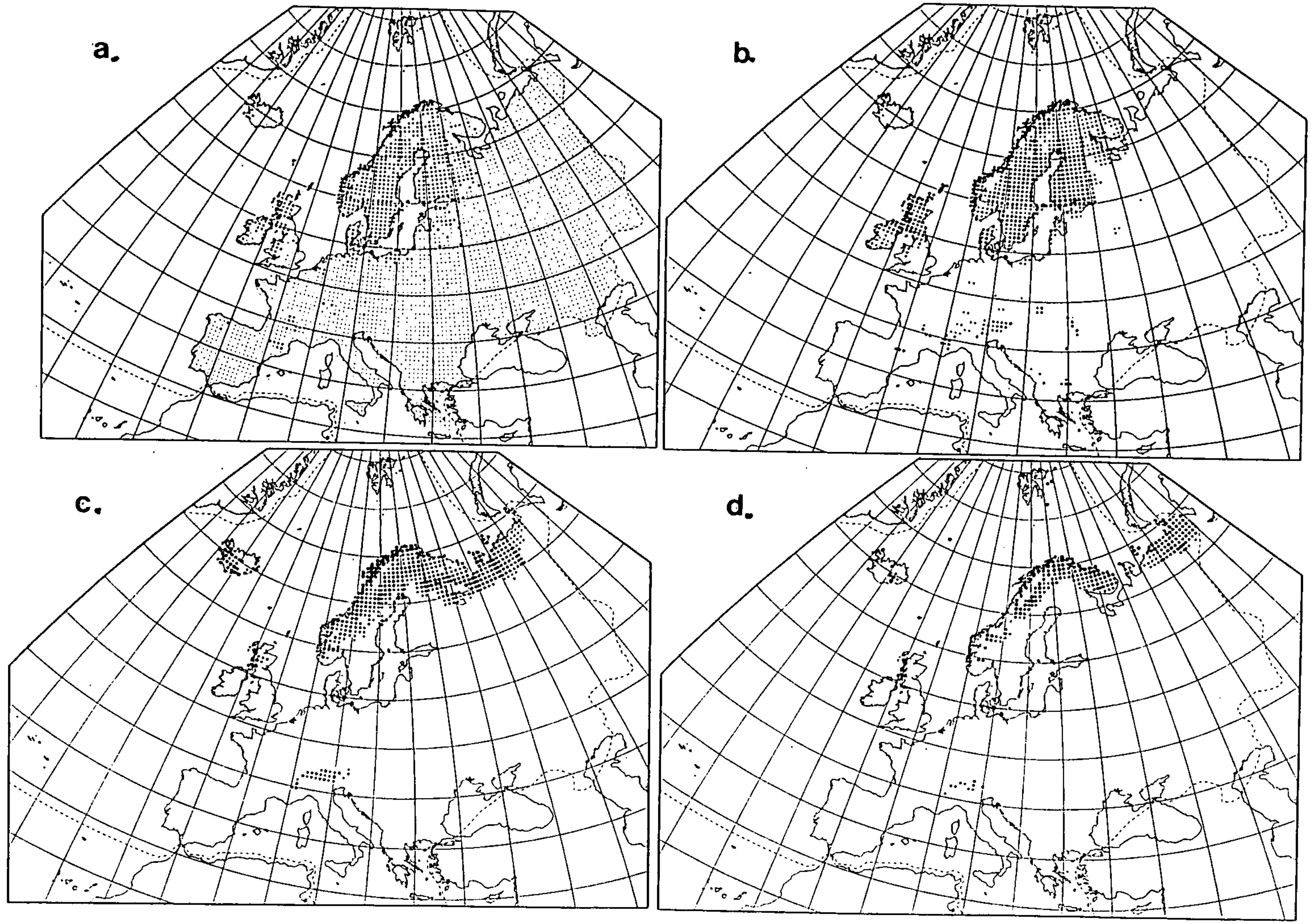

a.
b.
c.
d.

Figure 4.5

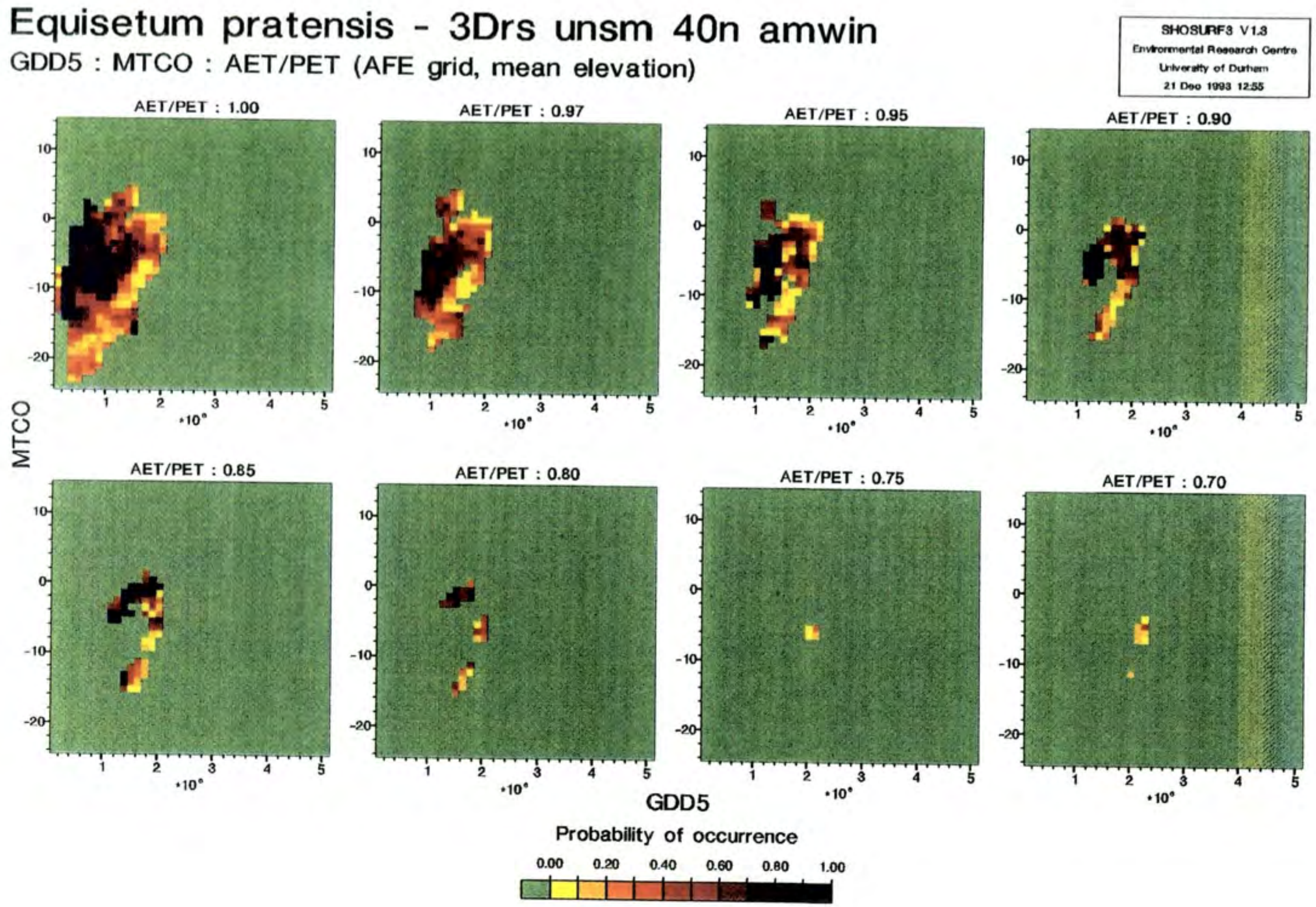

Equisetum pratensis - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
21 Dec 1993 12:55
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
AET/PET : 0.70
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.6 ***Equisetum pratensis***

a. AFE distribution

b. Normal simulation threshold probability 0.50

c. OSU simulation

d. UKMO simulation

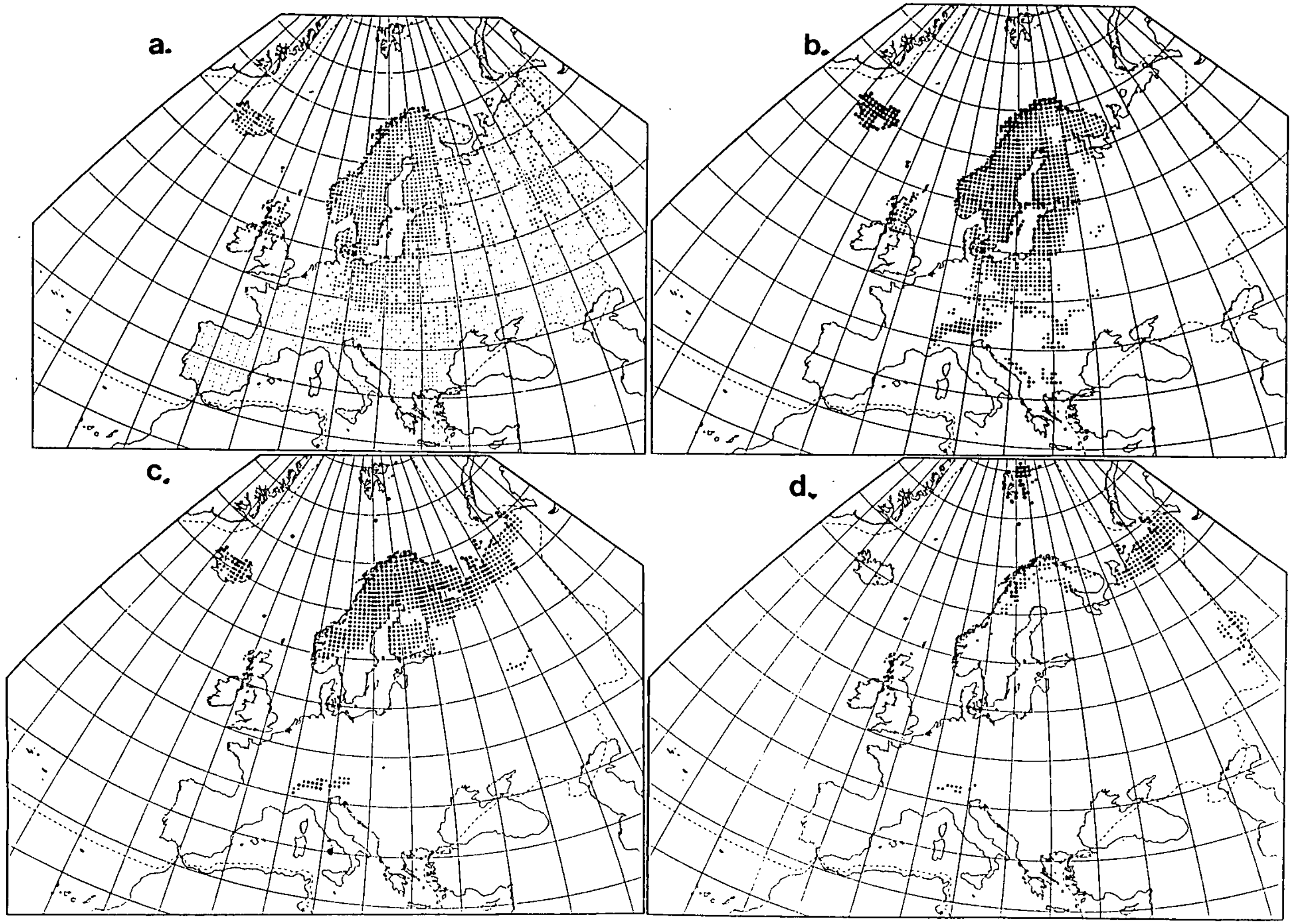
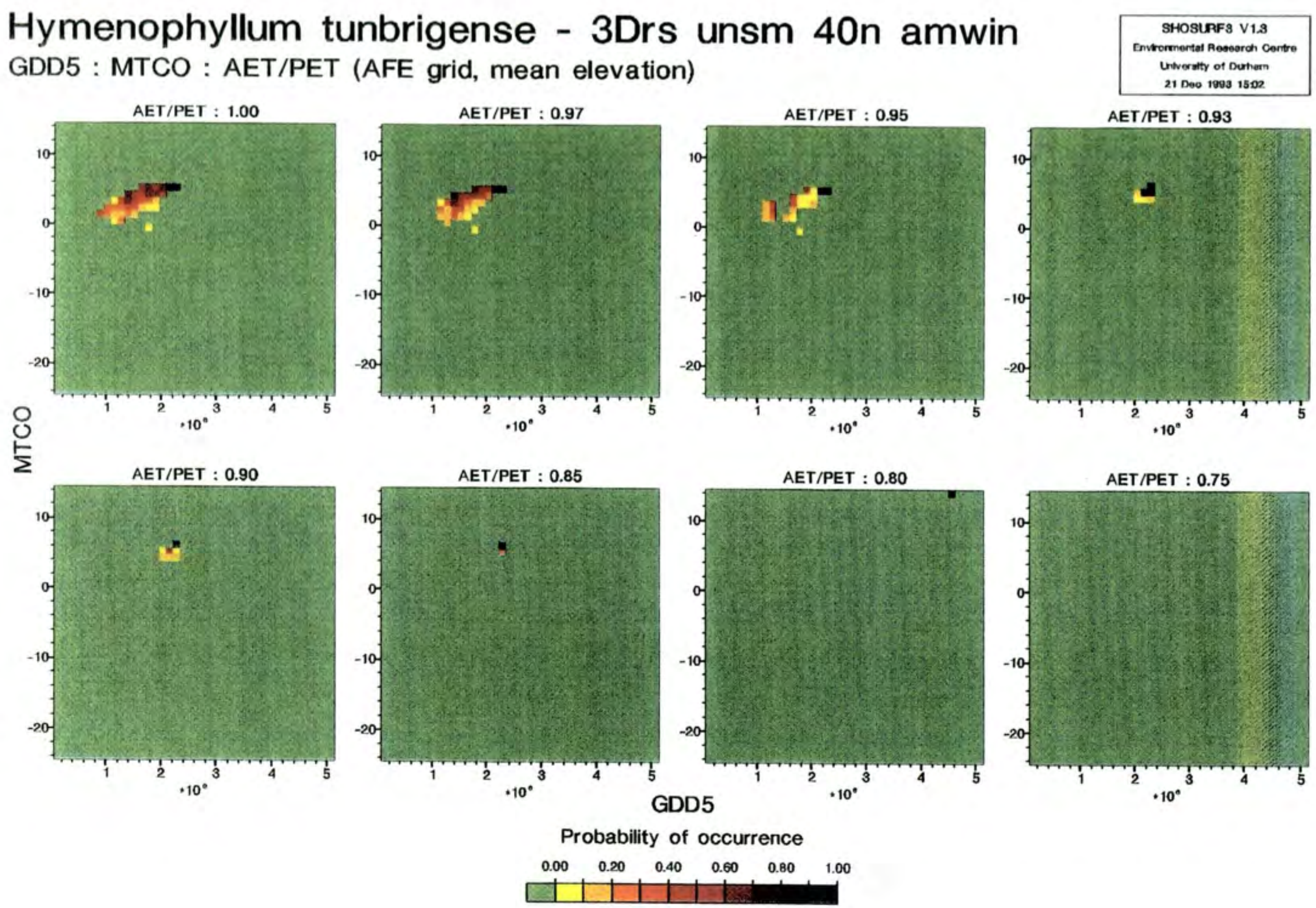

a.
b.
c.
d.

Figure 4.7



Hymenophyllum tunbrigense - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
21 Dec 1993 15:02
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.8 ***Hymenophyllum tunbrigense***

a. AFE distribution

b. Normal simulation threshold probability 0.30

c. OSU simulation

d. UKMO simulation

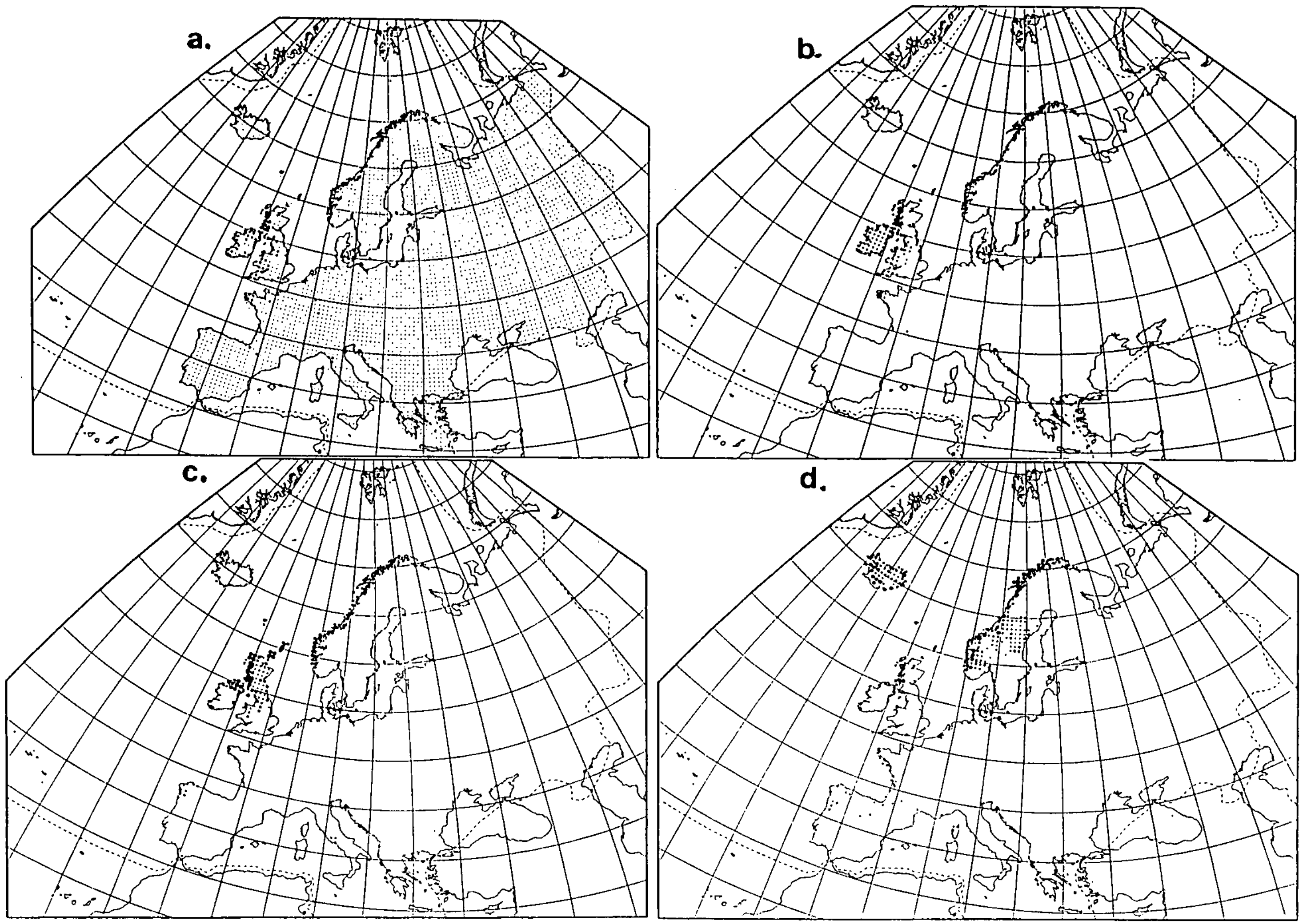


Figure 4.9

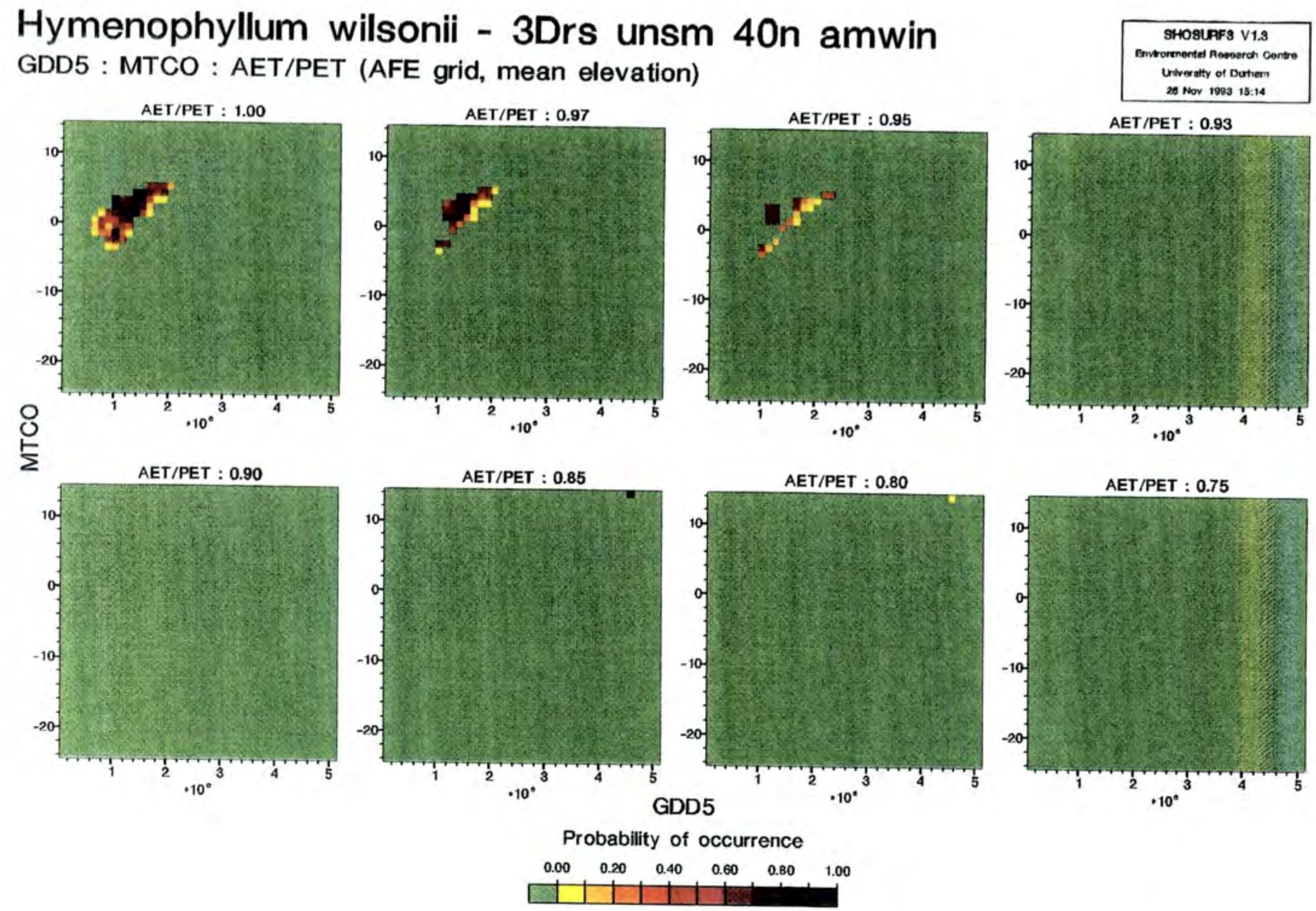

Hymenophyllum wilsonii - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
28 Nov 1993 15:14
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.10 ***Hymenophyllum wilsonii***

a. AFE distribution

b. Normal simulation threshold probability 0.40

c. OSU simulation

d. UKMO simulation

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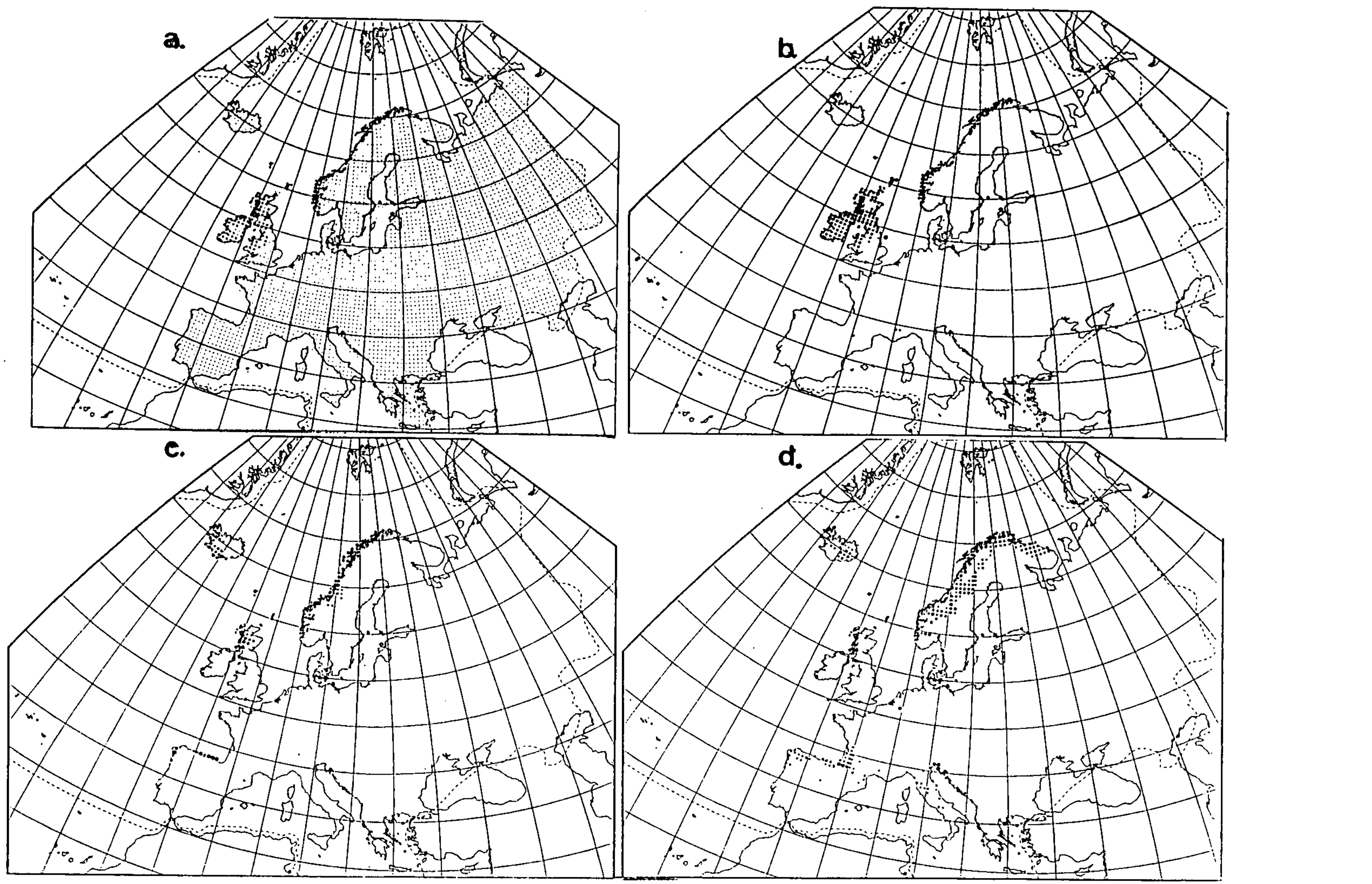
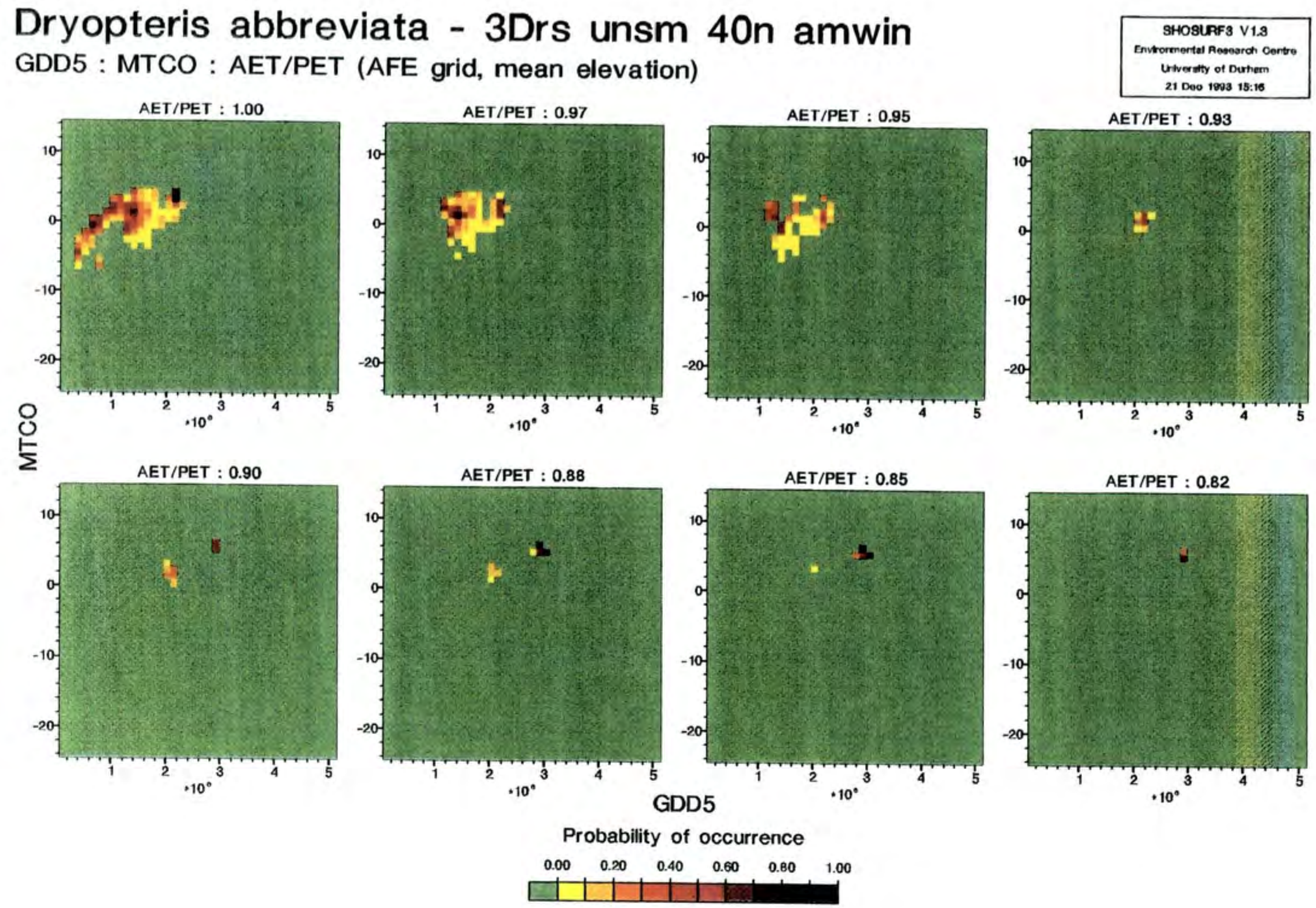

a.
b.
c.
d.

Figure 4.11



Dryopteris abbreviata - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
21 Dec 1993 15:16
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.88
AET/PET : 0.85
AET/PET : 0.82
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.12 ***Dryopteris abbreviata***

a. AFE distribution

b. Normal simulation threshold probability 0.20

c. OSU simulation

d. UKMO simulation

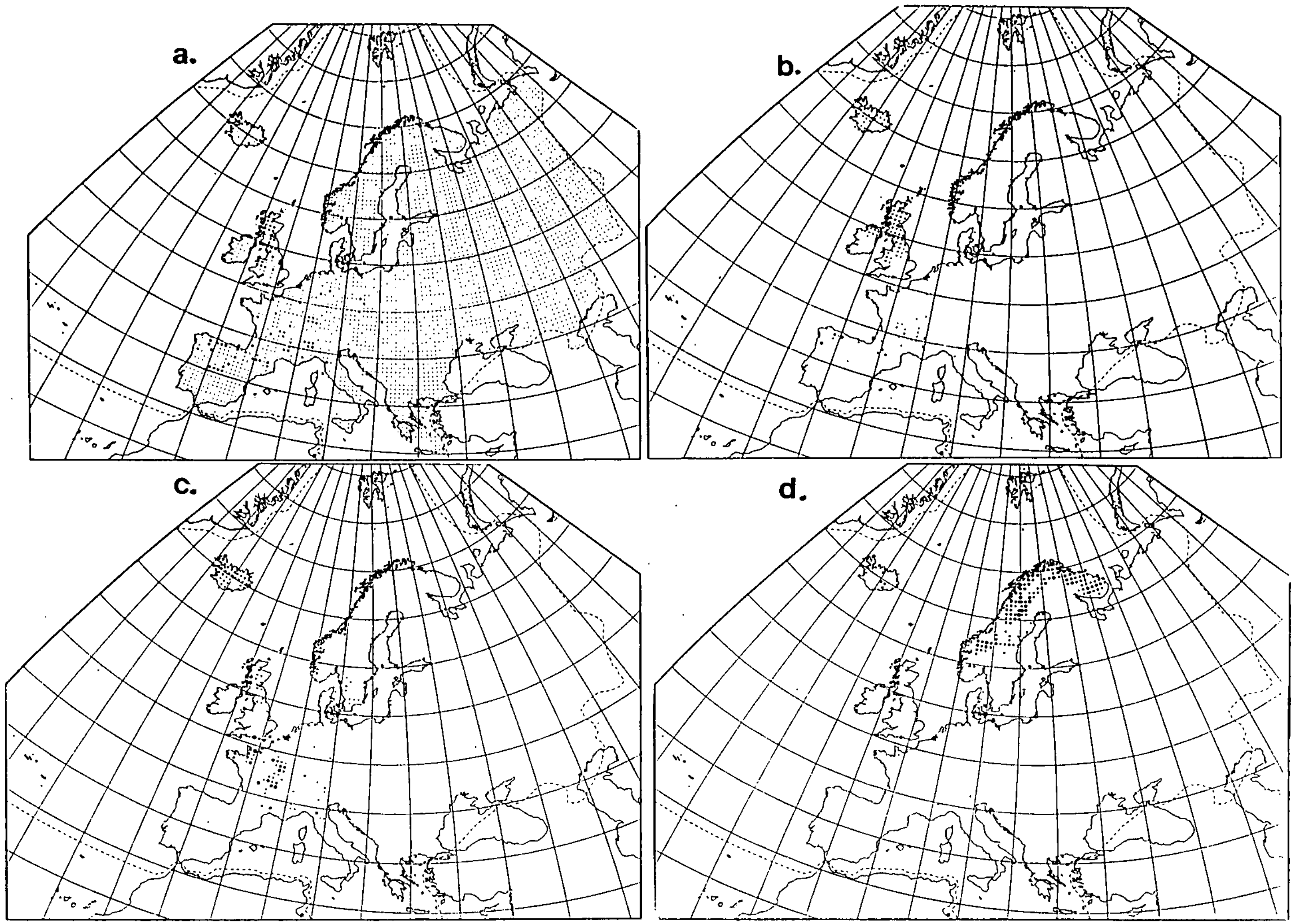
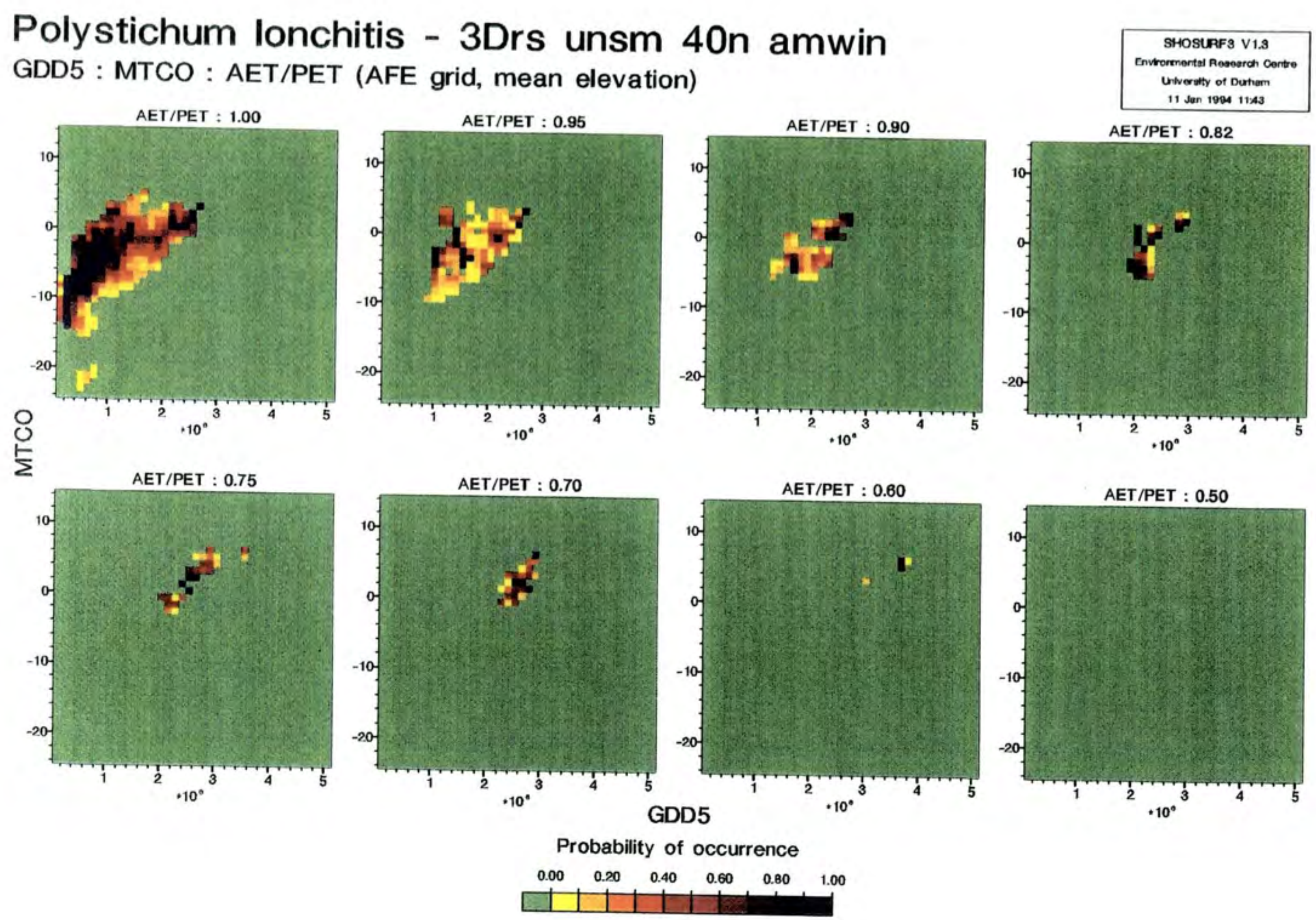

a.
b.
c.
d.

Figure 4.13



Polystichum lonchitis - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
11 Jan 1994 11:43
AET/PET : 1.00
AET/PET : 0.95
AET/PET : 0.90
AET/PET : 0.82
AET/PET : 0.75
AET/PET : 0.70
AET/PET : 0.60
AET/PET : 0.50
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.14 *Polystichum lonchitis*

a. AFE distribution

b. Normal simulation threshold probability 0.30

c. OSU simulation

d. UKMO simulation

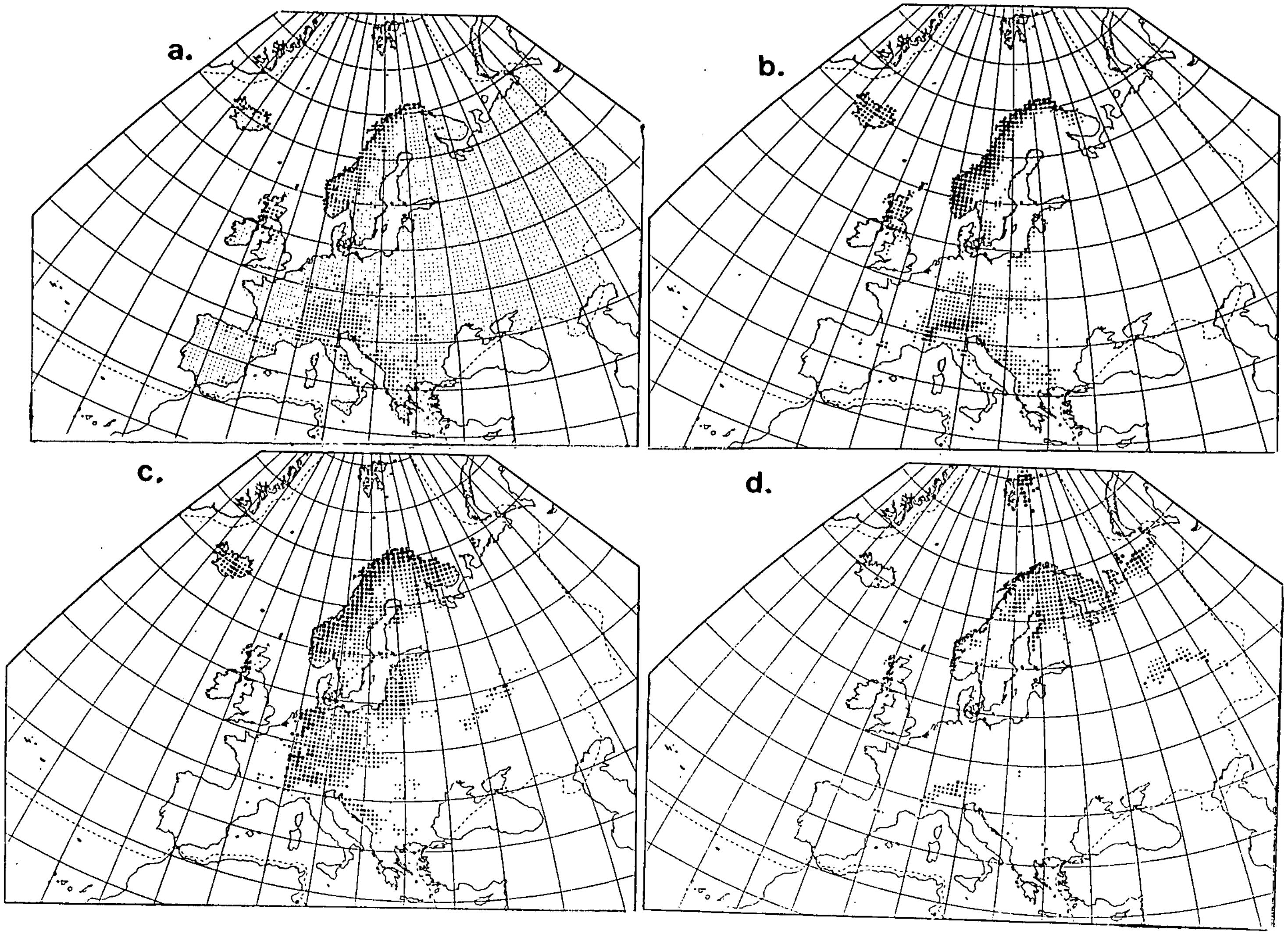

a.
b.
c.
d.

Figure 4.15

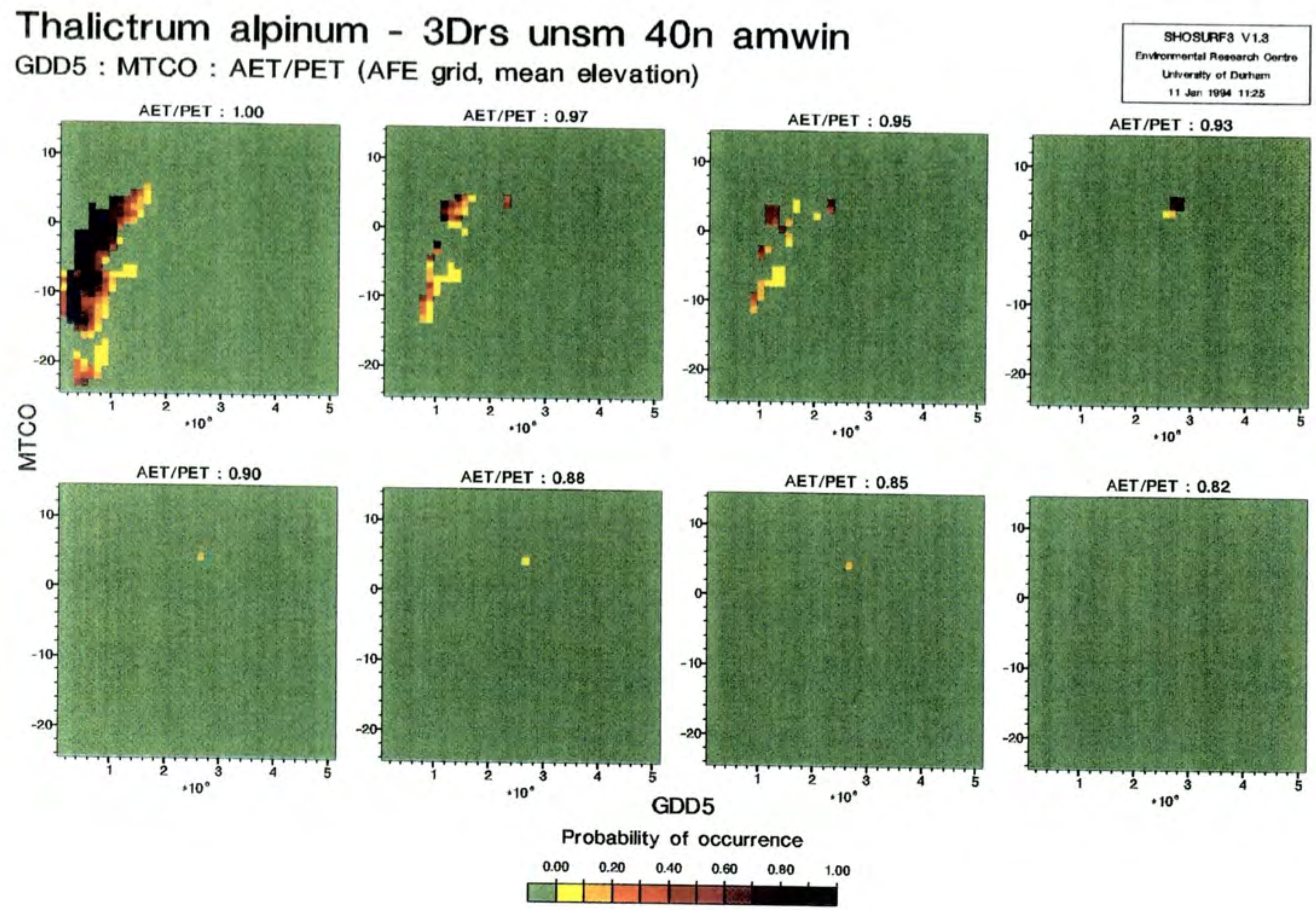

Thalictrum alpinum - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
11 Jan 1994 11:25
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.88
AET/PET : 0.85
AET/PET : 0.82
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.16 ***Thalictrum alpinum***

a. AFE distribution

b. Normal simulation threshold probability 0.30

c. OSU simulation

d. UKMO simulation

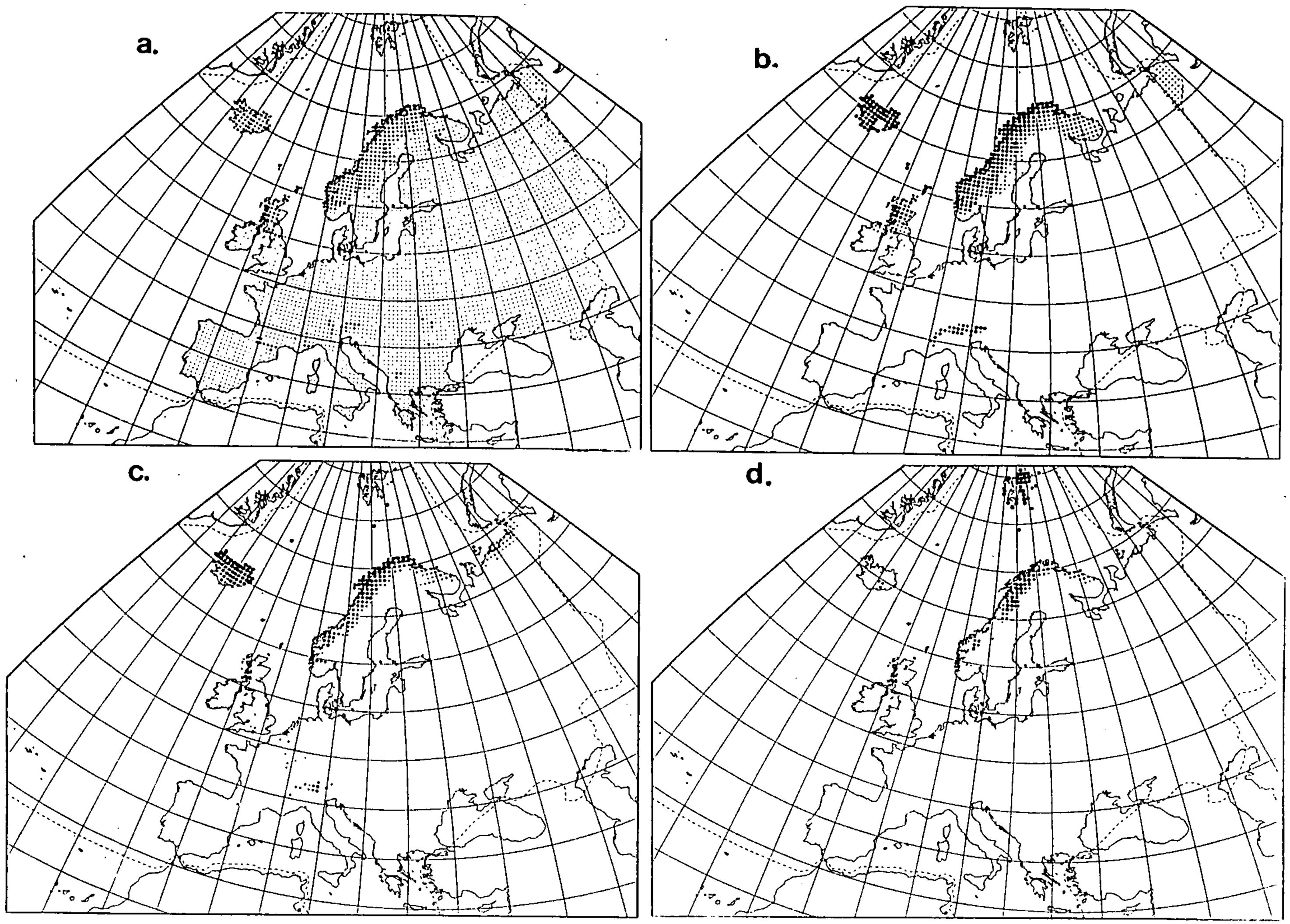

a.
b.
c.
d.

Figure 4.17

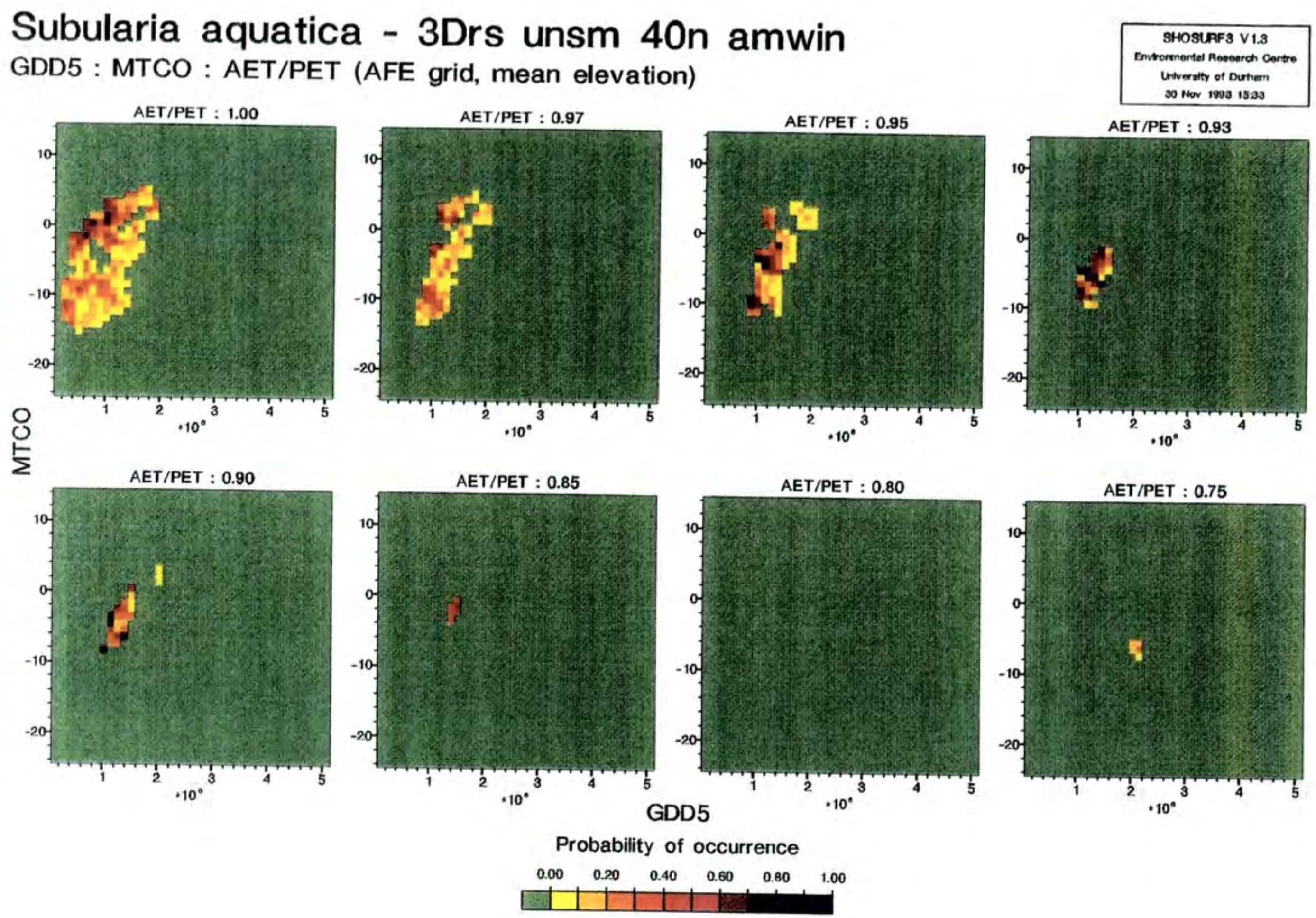

Subularia aquatica - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
30 Nov 1993 15:33
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.18 ***Subularia aquatica***

a. AFE distribution

b. Normal simulation threshold probability 0.20

c. OSU simulation

d. UKMO simulation

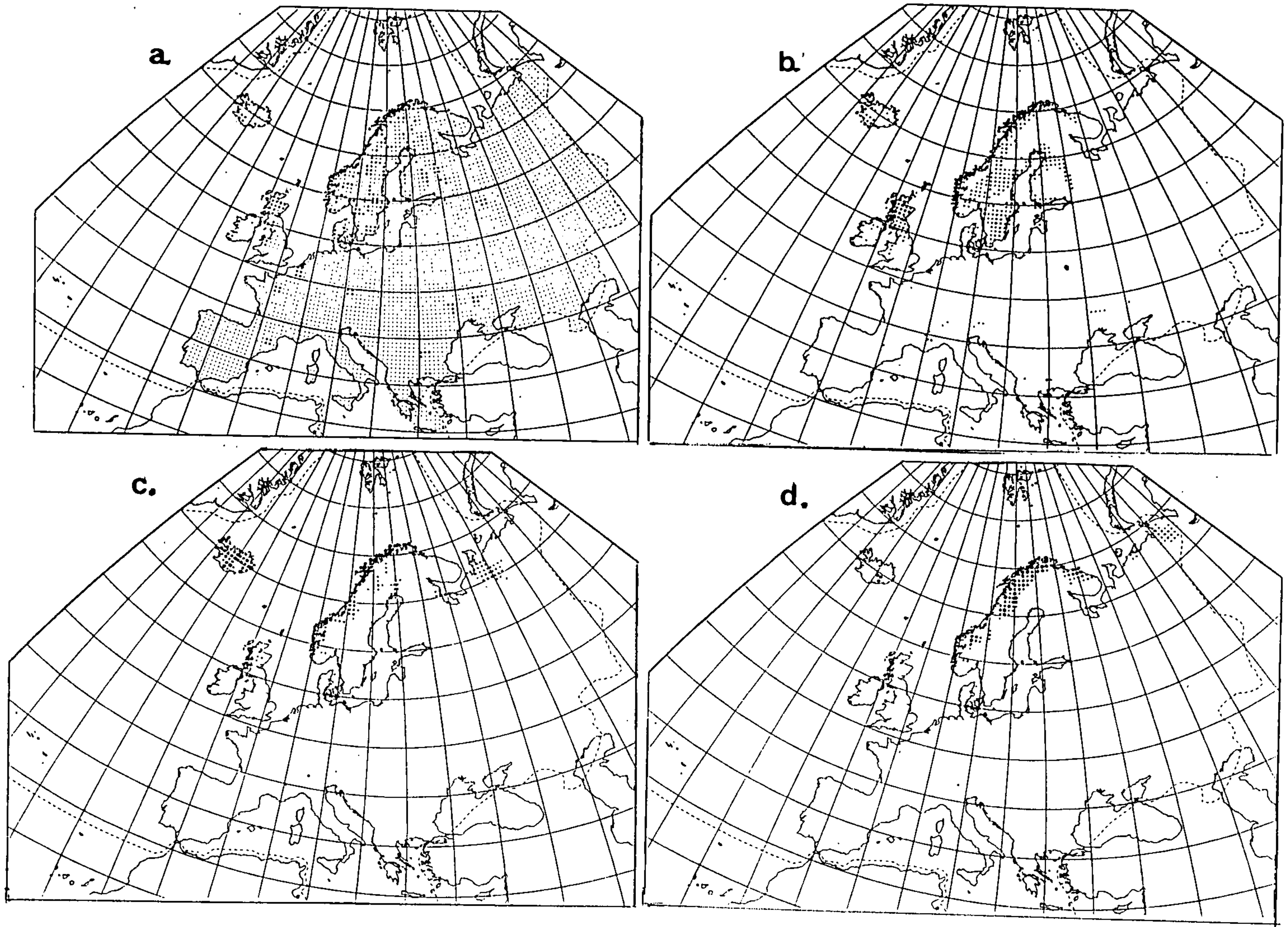

a.
b.
c.
d.

Figure 4.19

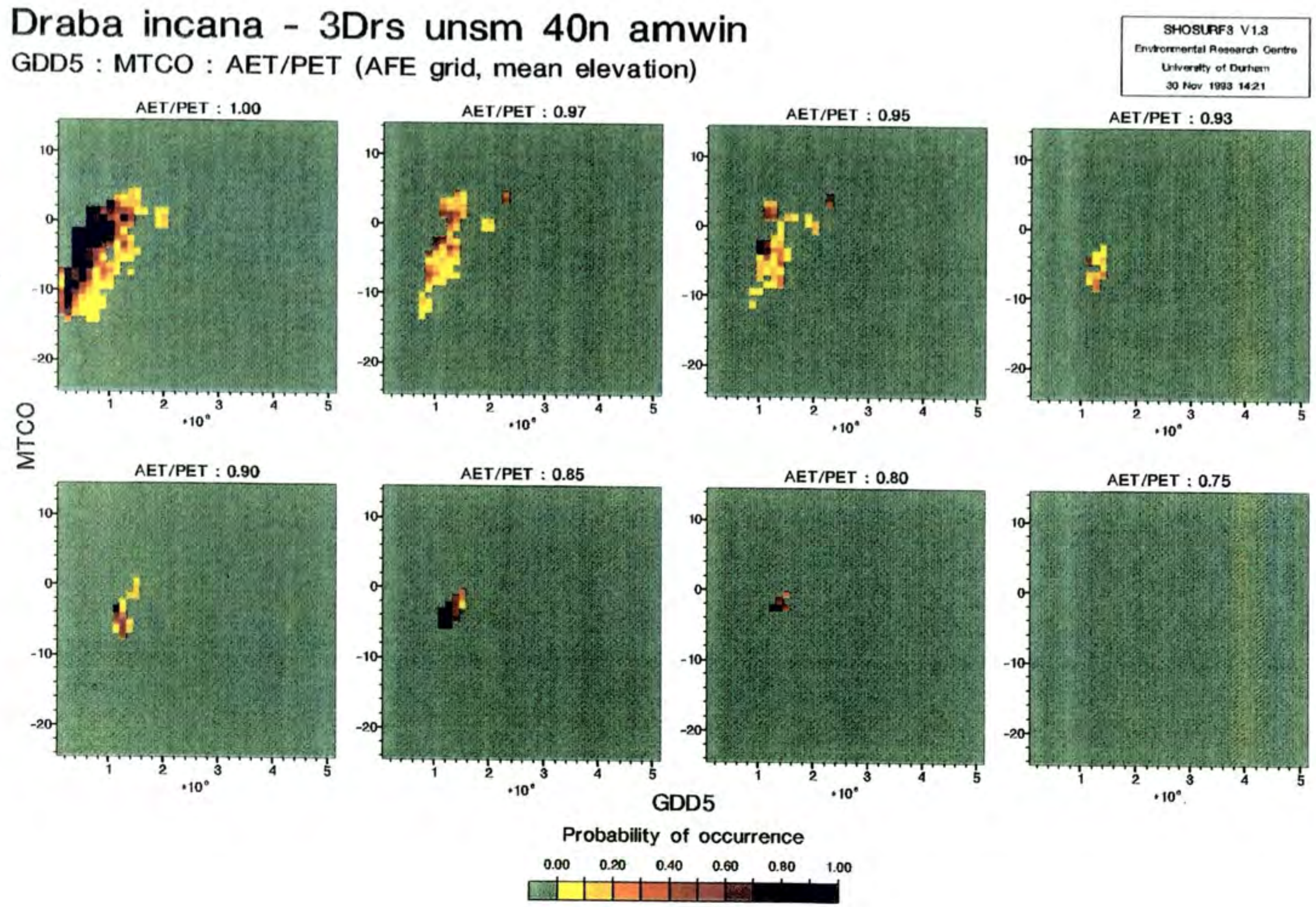

Draba incana - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
30 Nov 1993 14:21
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.20 ***Draba incana***

a. AFE distribution

b. Normal simulation threshold probability 0.30

c. OSU simulation

d. UKMO simulation

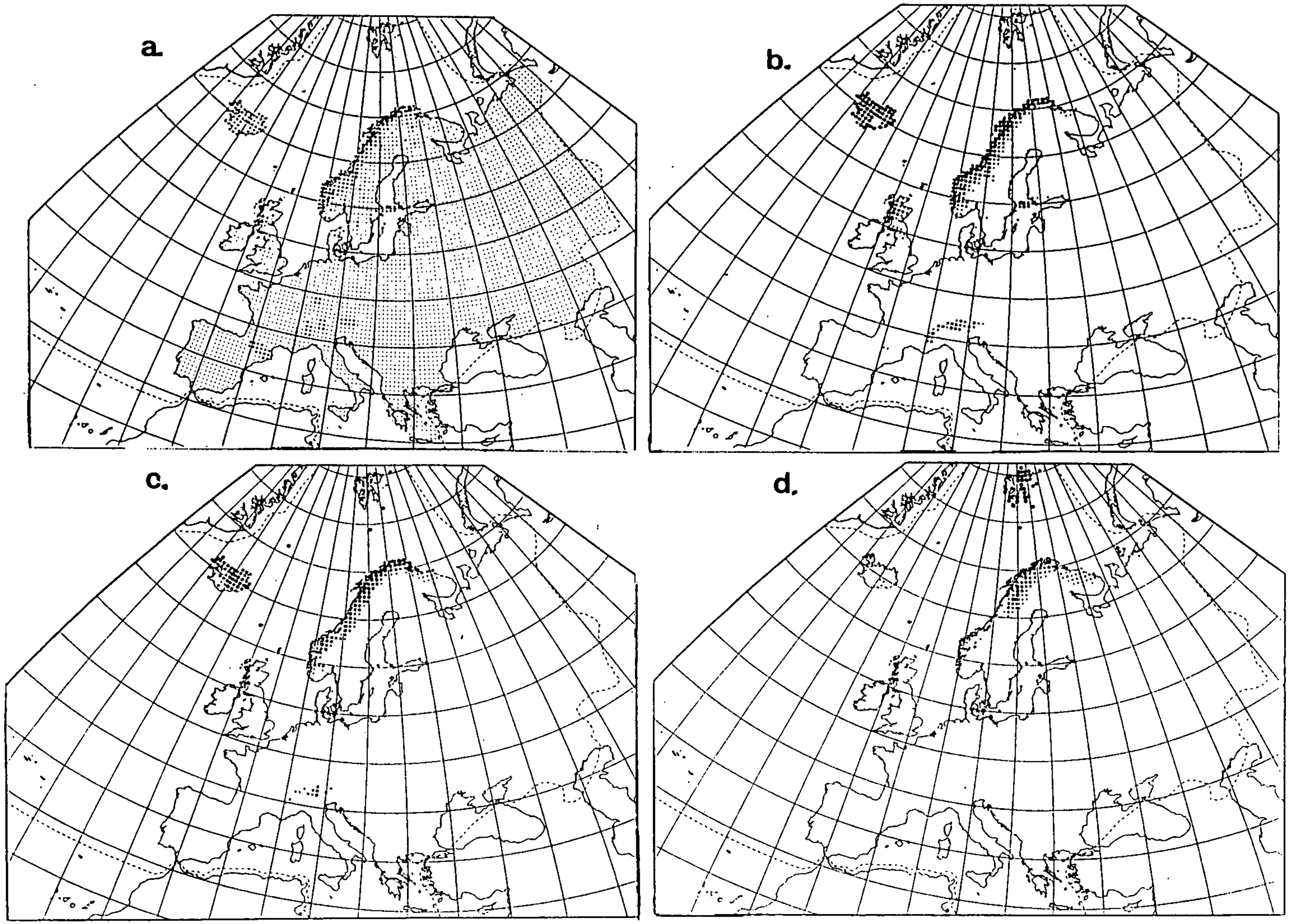

a.
b.
c.
d.

Figure 4.21

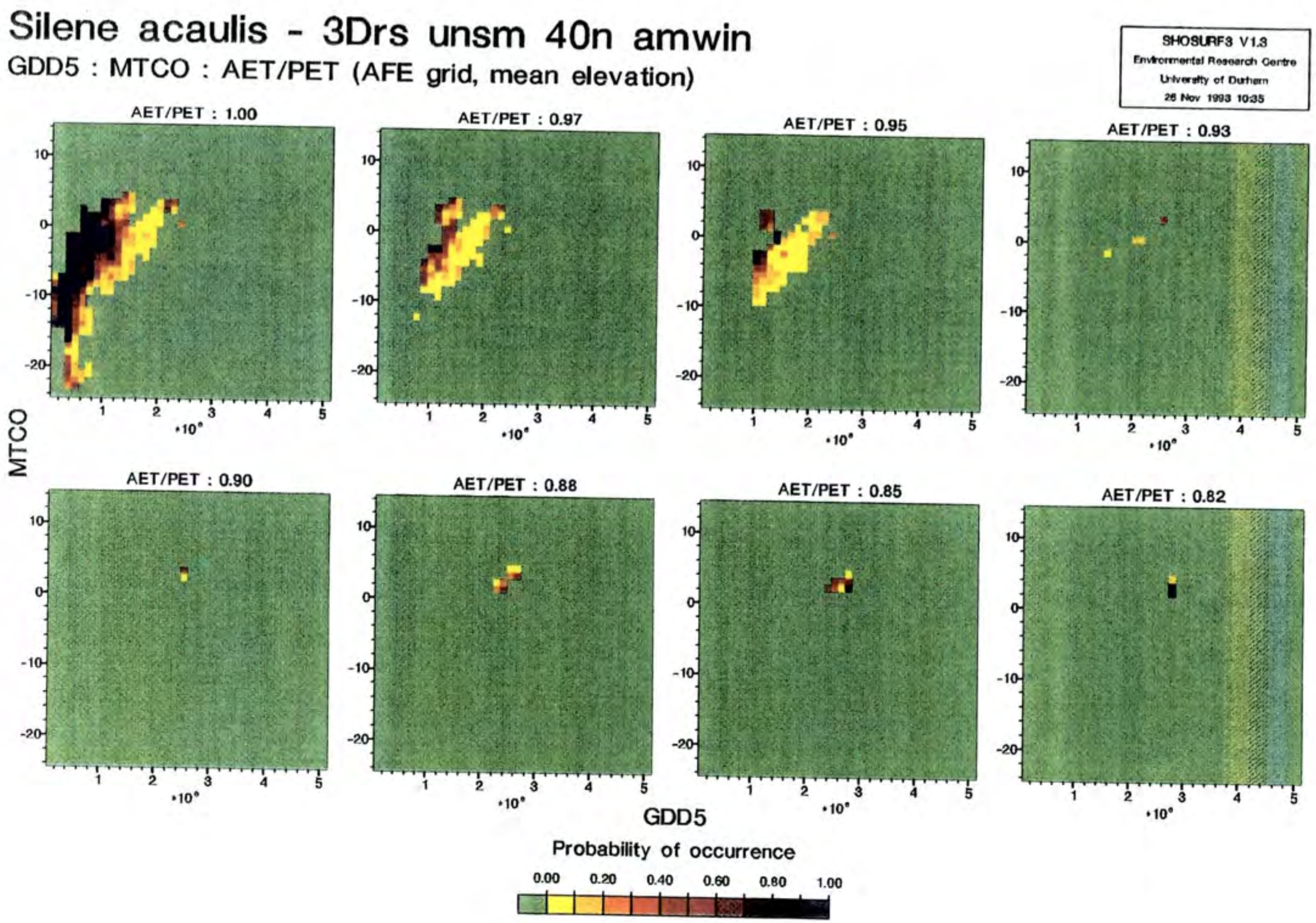

Silene acaulis - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
26 Nov 1993 10:35
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.88
AET/PET : 0.85
AET/PET : 0.82
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.22 ***Silene acaulis***

a. AFE distribution

b. Normal simulation threshold probability 0.25

c. OSU simulation

d. UKMO simulation

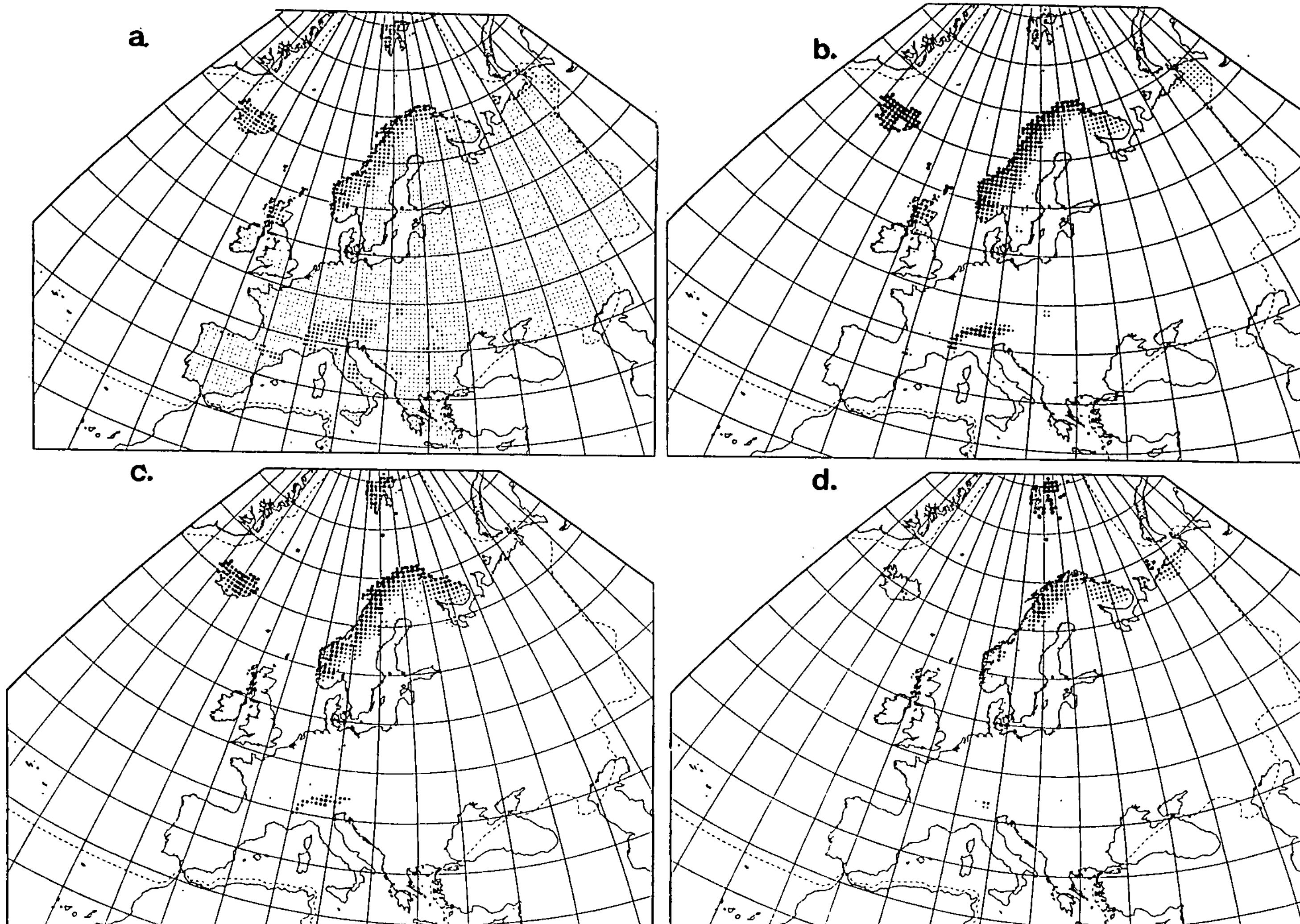

a.
b.
c.
d.

Figure 4.23

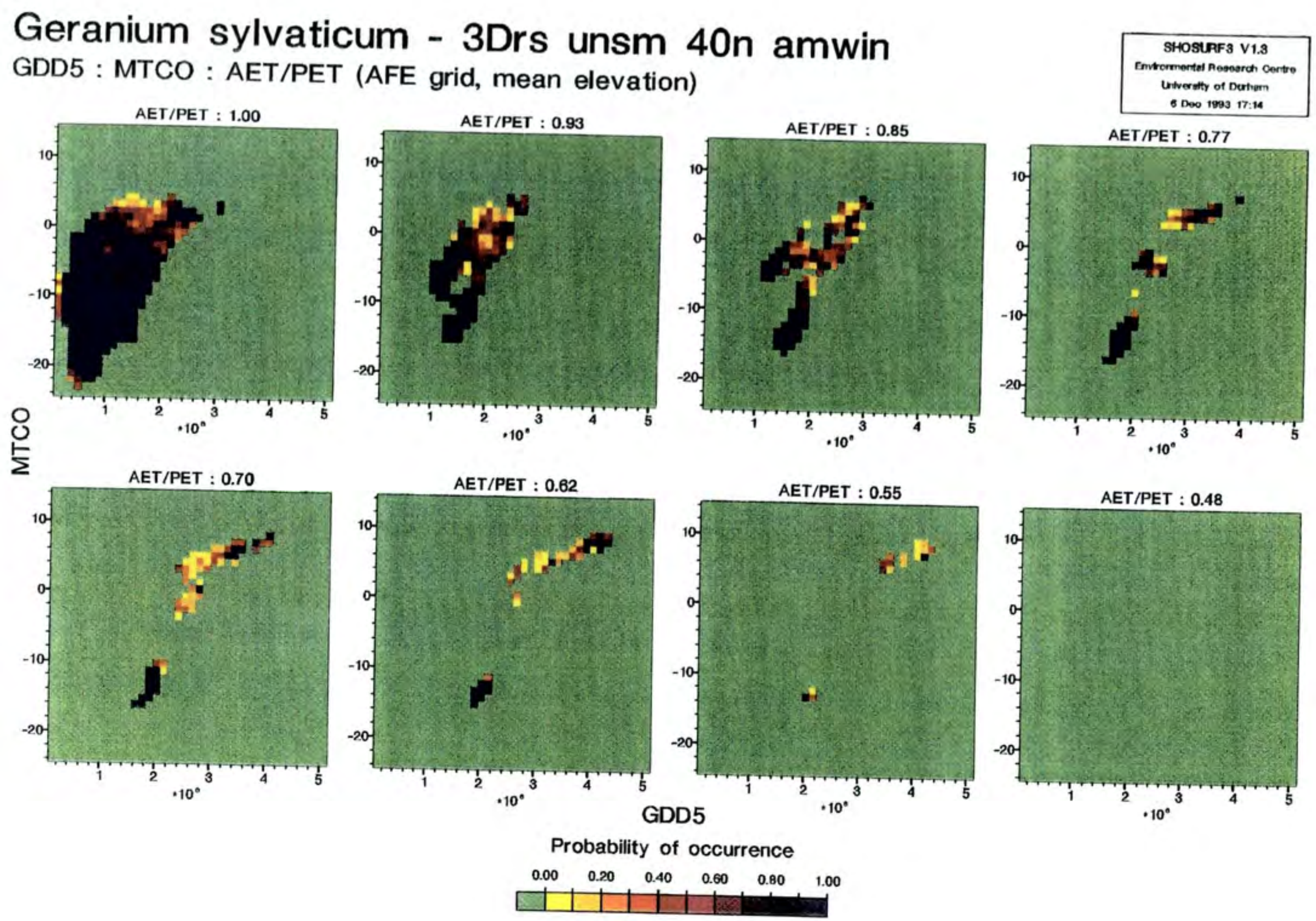

Geranium sylvaticum - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
6 Dec 1993 17:14
AET/PET : 1.00
AET/PET : 0.93
AET/PET : 0.85
AET/PET : 0.77
AET/PET : 0.70
AET/PET : 0.62
AET/PET : 0.55
AET/PET : 0.48
MTCO
GDD5
*10³
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

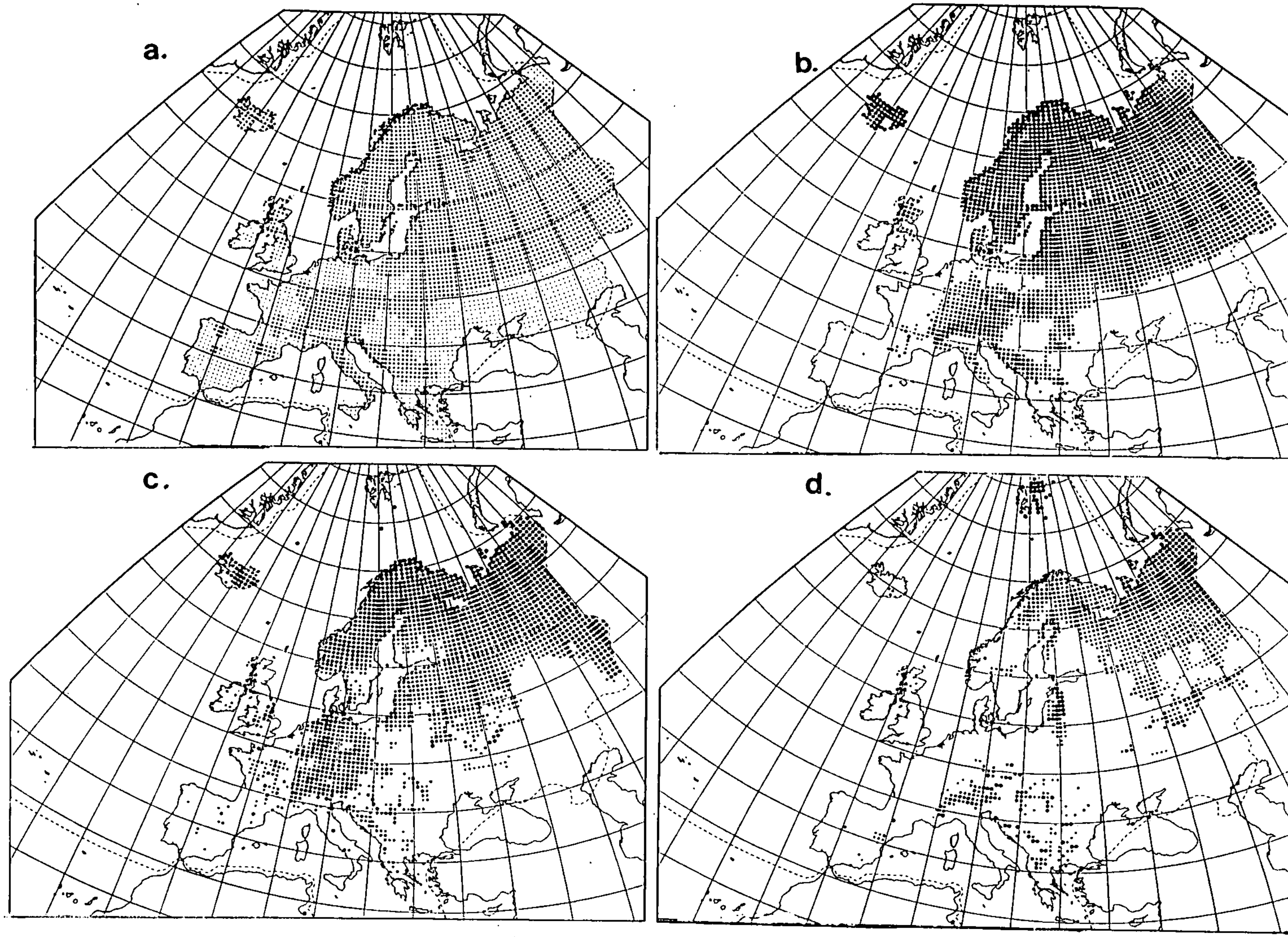
Figure 4.24 ***Geranium sylvaticum***

a. AFE distribution

b. Normal simulation threshold probability 0.50

c. OSU simulation

d. UKMO simulation



a.
b.
c.
d.

Figure 4.25

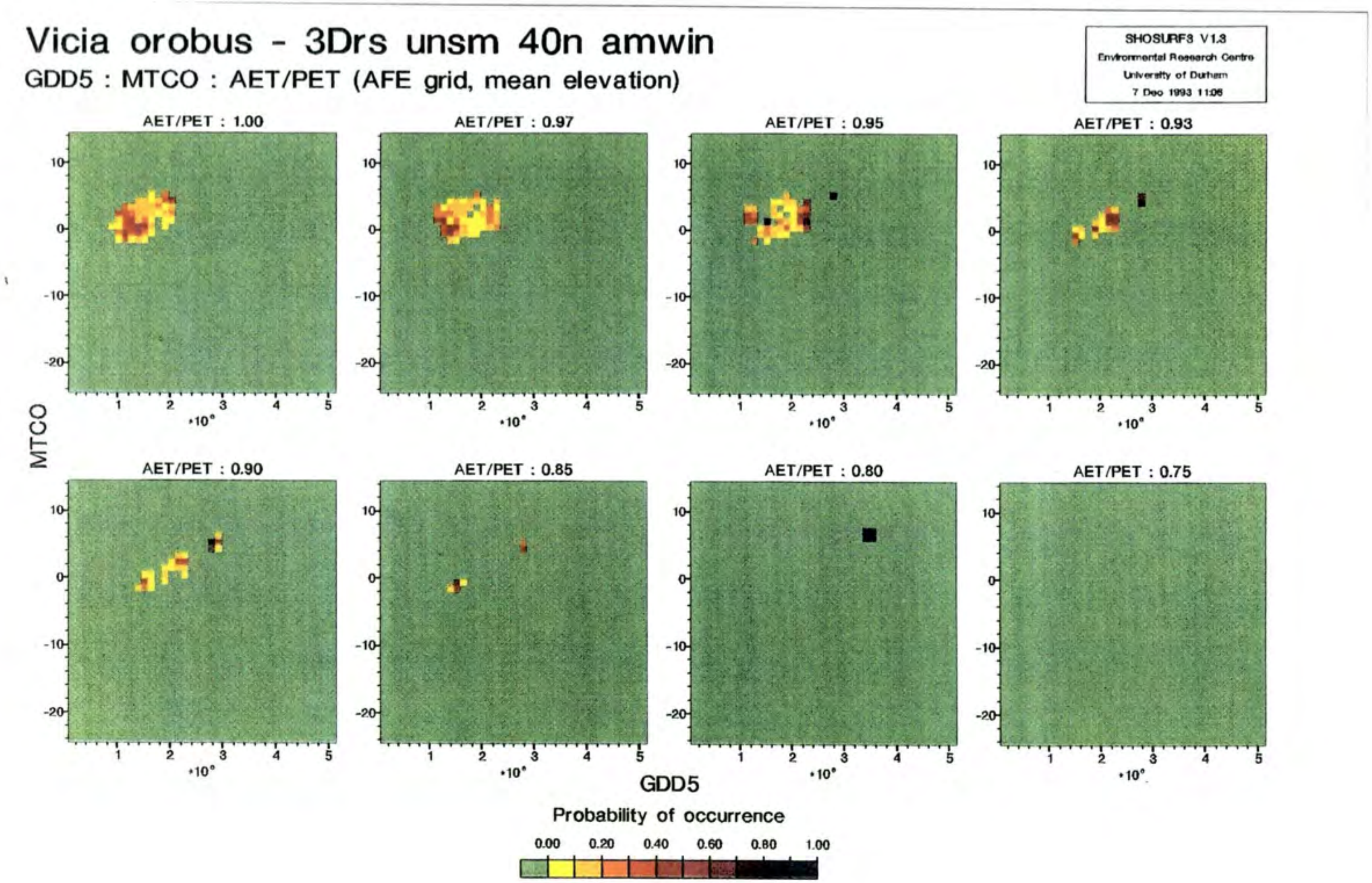

Vicia orobus - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
7 Dec 1993 11:06
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.26 ***Vicia orobus***

a. AFE distribution

b. Normal simulation threshold probability 0.20

c. OSU simulation

d. UKMO simulation

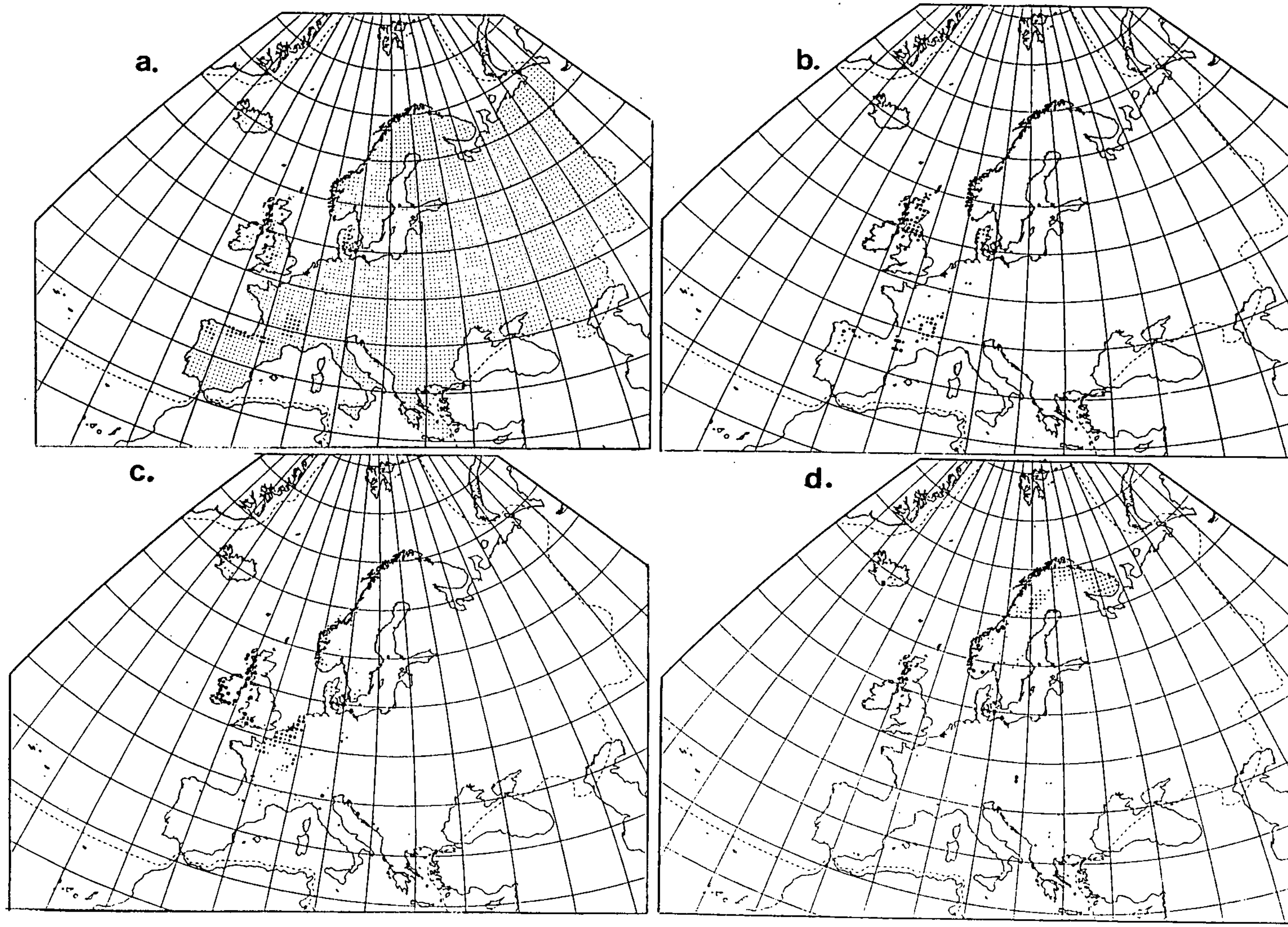

a.
b.
c.
d.

Figure 4.27

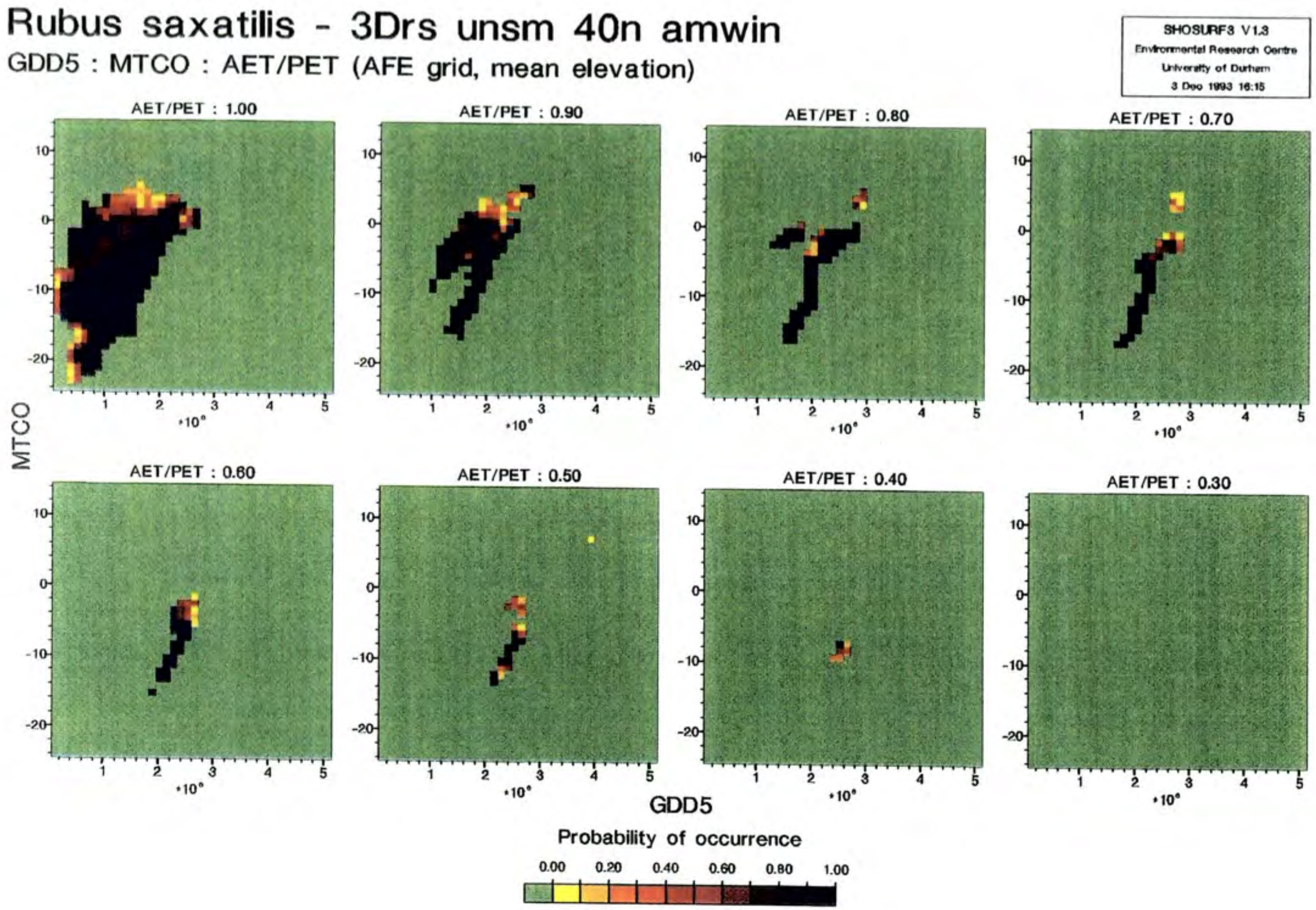

Rubus saxatilis - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 16:15
AET/PET : 1.00
AET/PET : 0.90
AET/PET : 0.80
AET/PET : 0.70
AET/PET : 0.60
AET/PET : 0.50
AET/PET : 0.40
AET/PET : 0.30
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

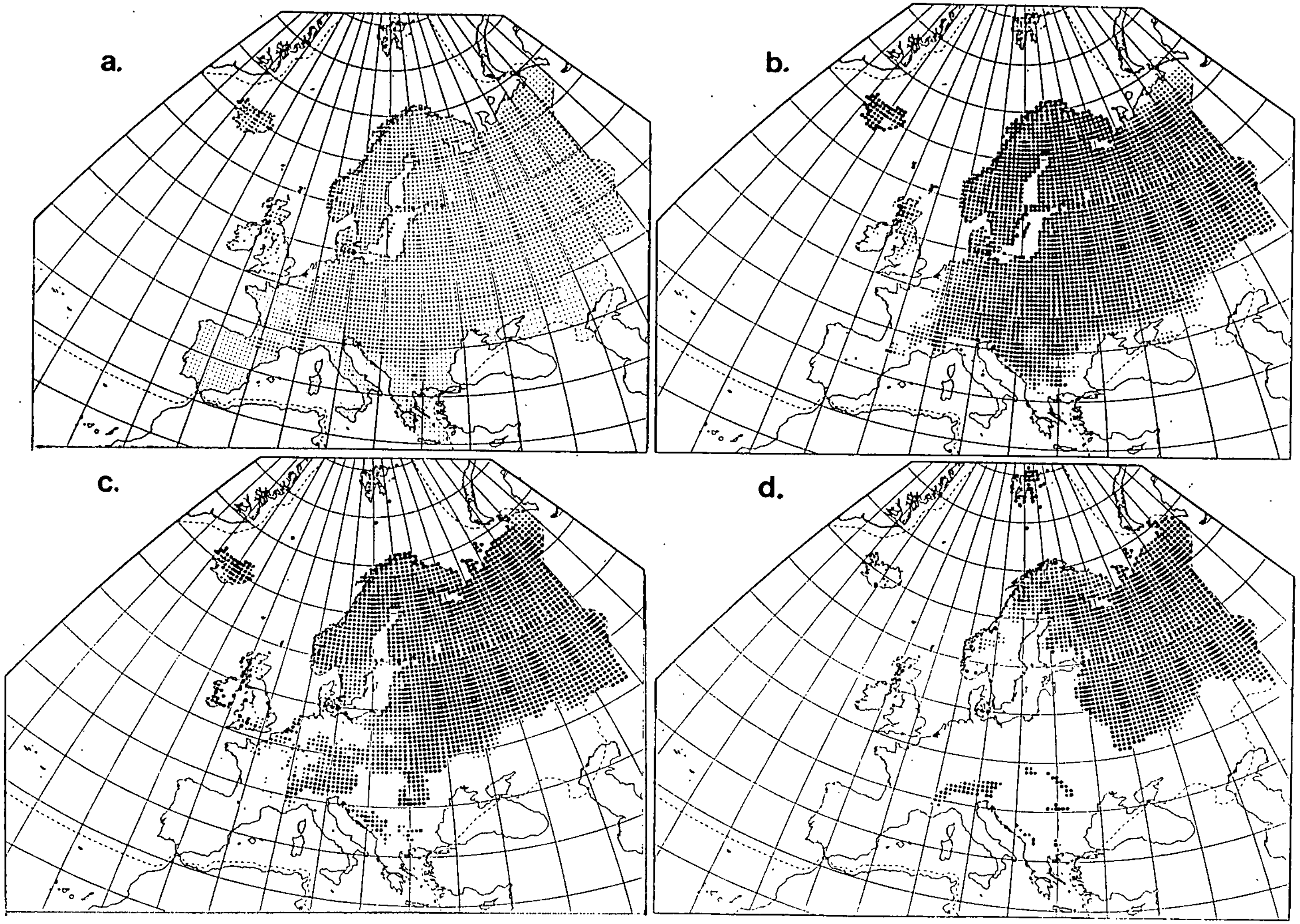
Figure 4.28 *Rubus saxatilis*

a. AFE distribution

b. Normal simulation threshold probability 0.30

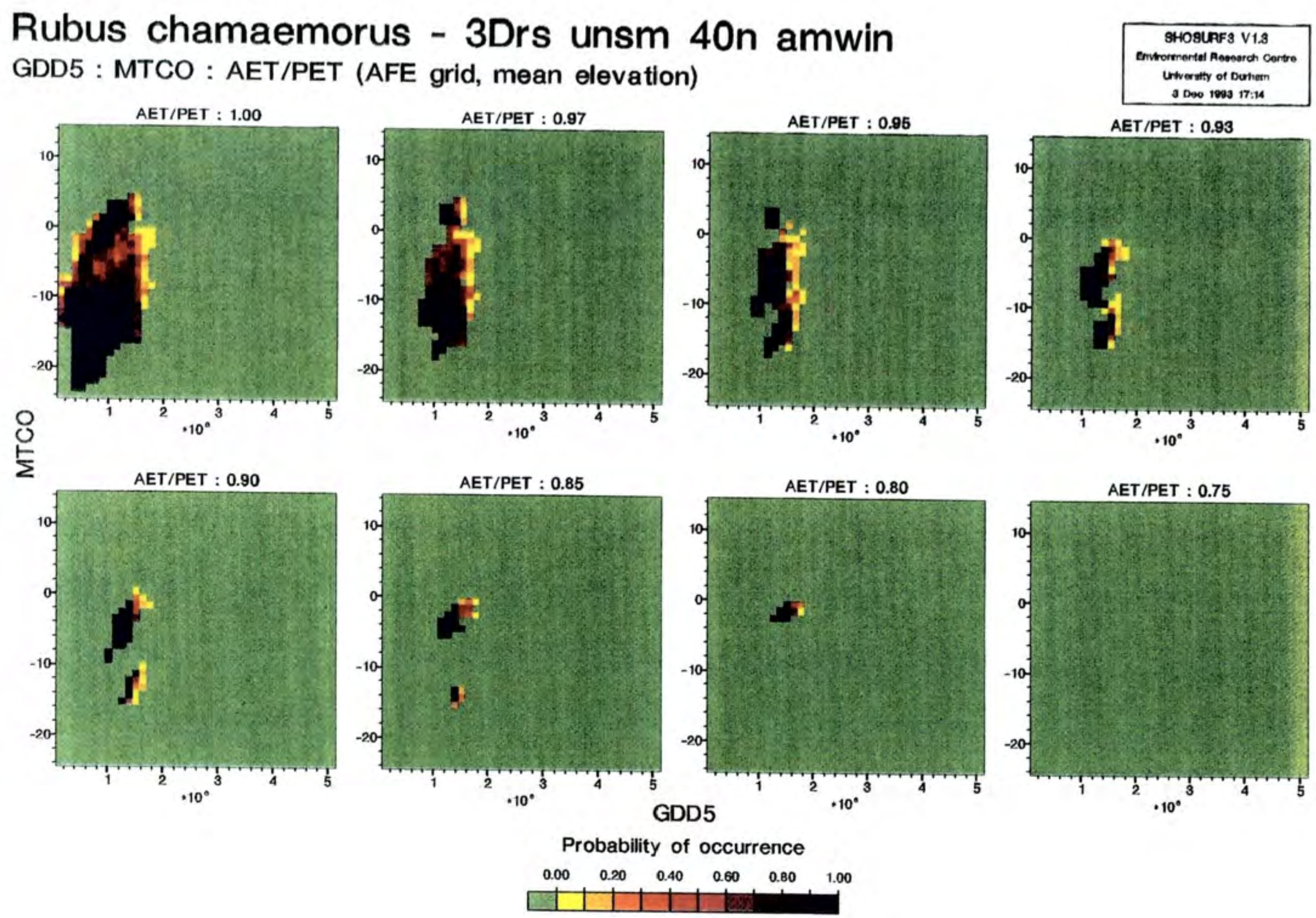
c. OSU simulation

d. UKMO simulation



a.
b.
c.
d.

Figure 4.29



Rubus chamaemorus - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 17:14
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.30 ***Rubus chamaemorus***

a. AFE distribution

b. Normal simulation threshold probability 0.50

c. OSU simulation

d. UKMO simulation

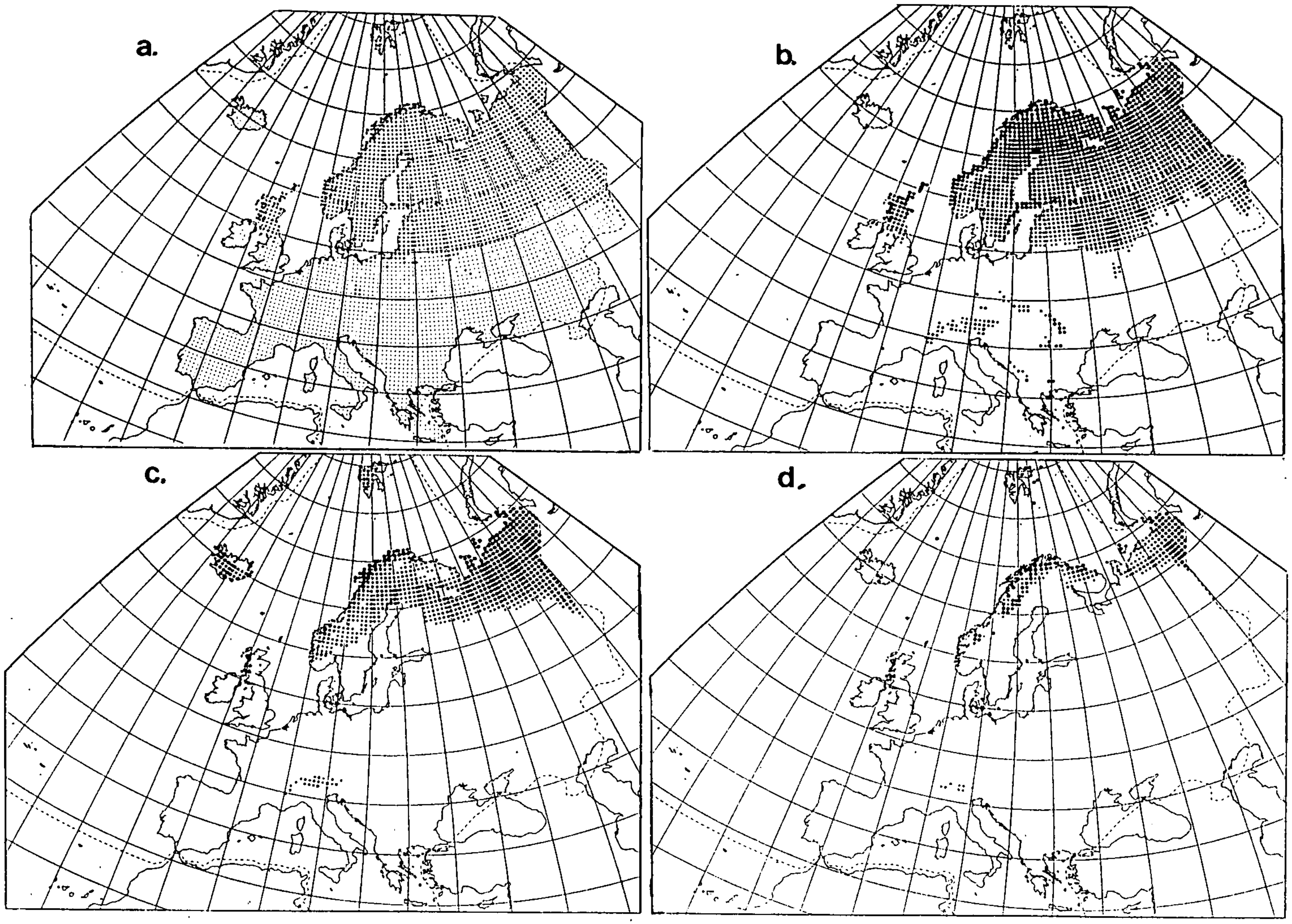

a.
b.
c.
d.

Figure 4.31

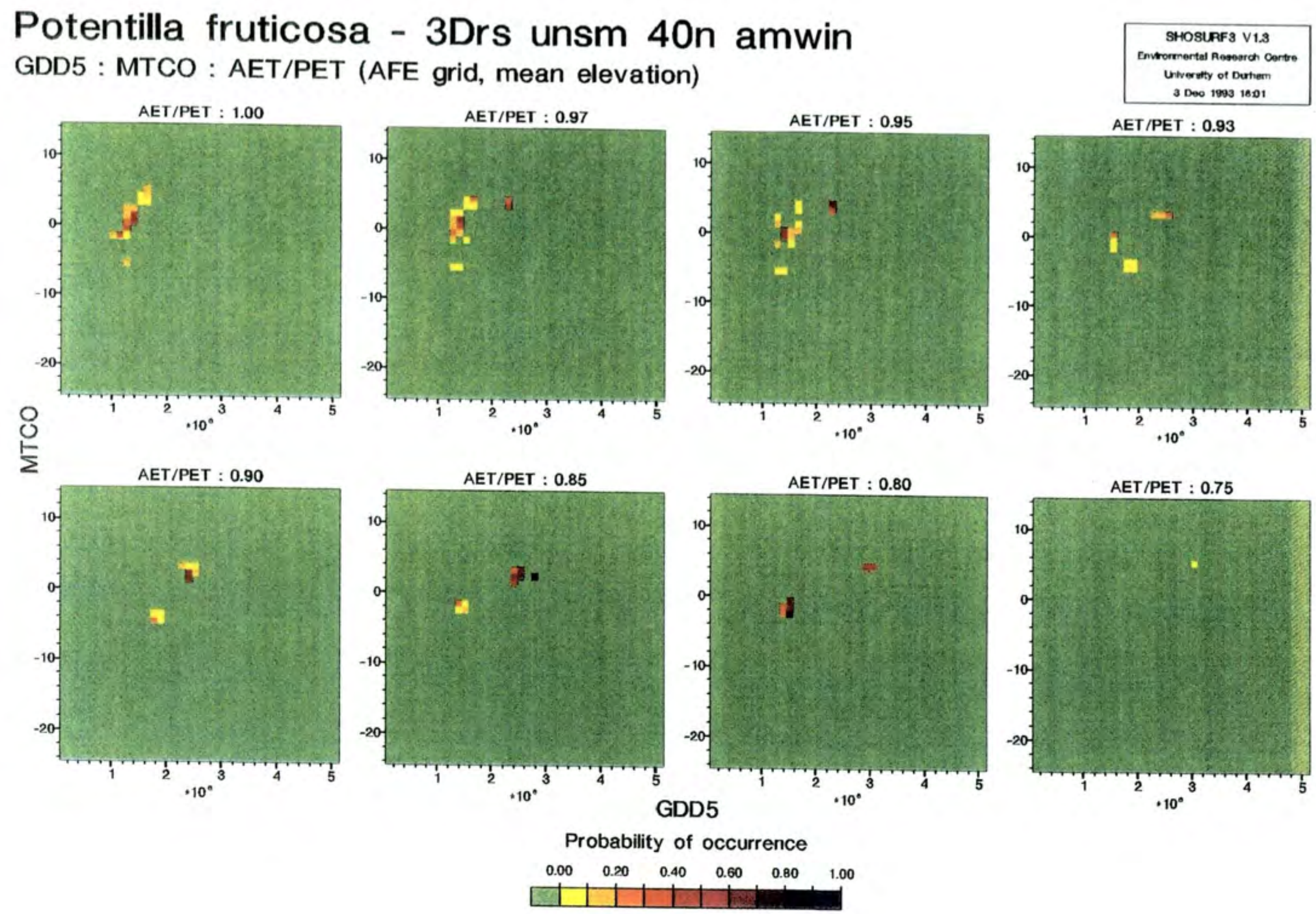

Potentilla fruticosa - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 18:01
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.32 ***Potentilla fruticosa***

a. AFE distribution

b. Normal simulation threshold probability 0.15

c. OSU simulation

d. UKMO simulation

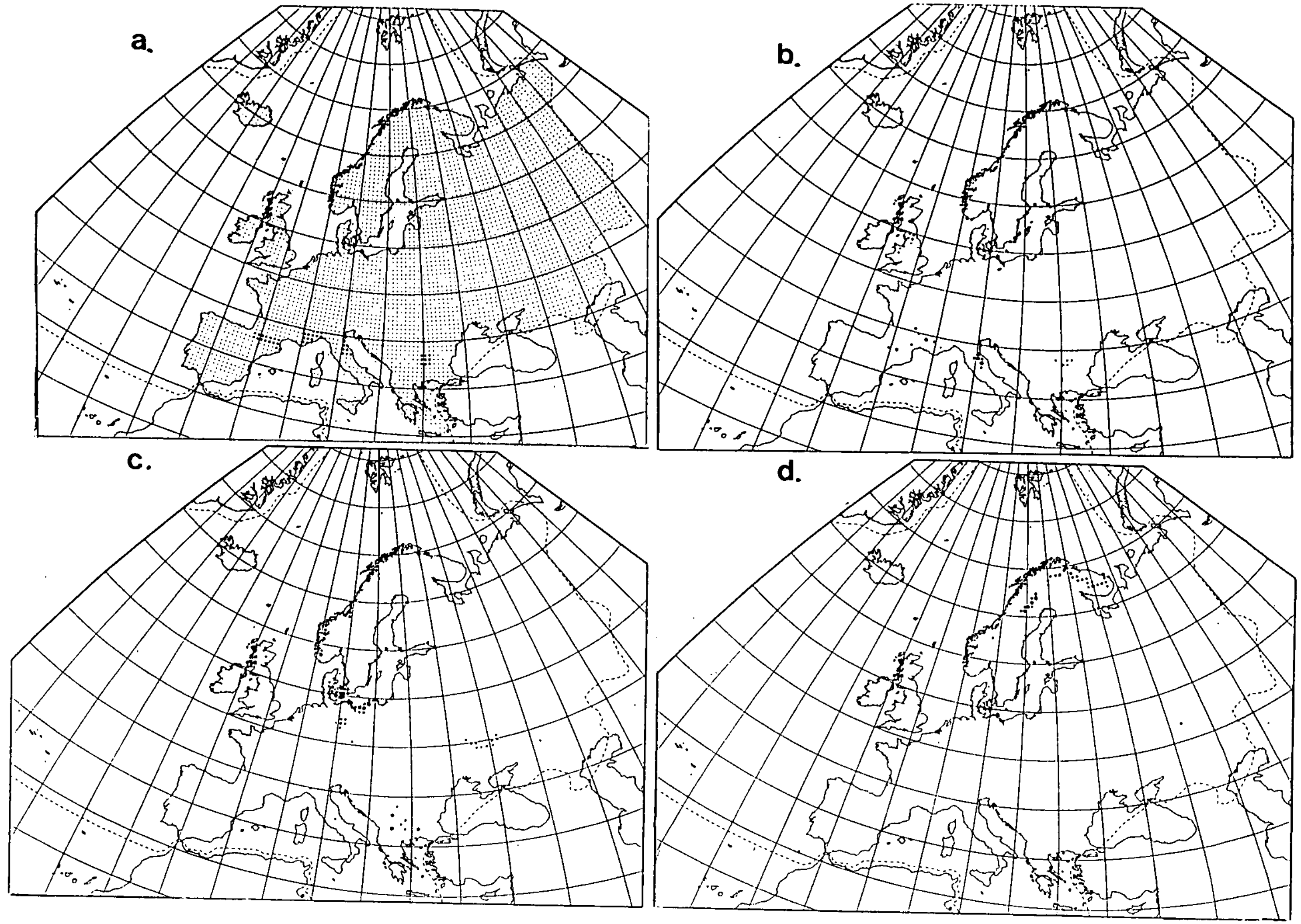
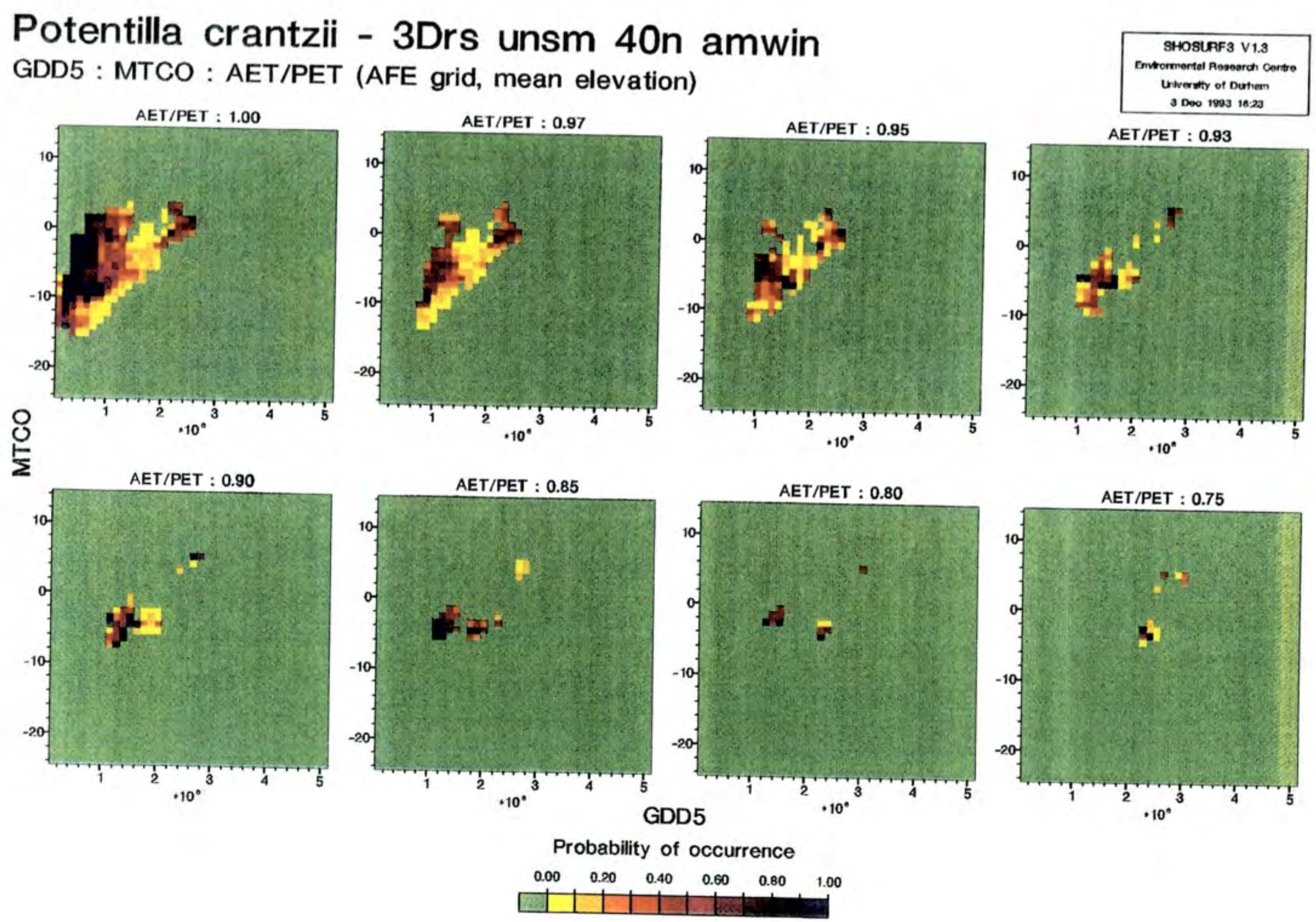

a.
b.
c.
d.

Figure 4.33



Potentilla crantzii - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 16:23
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

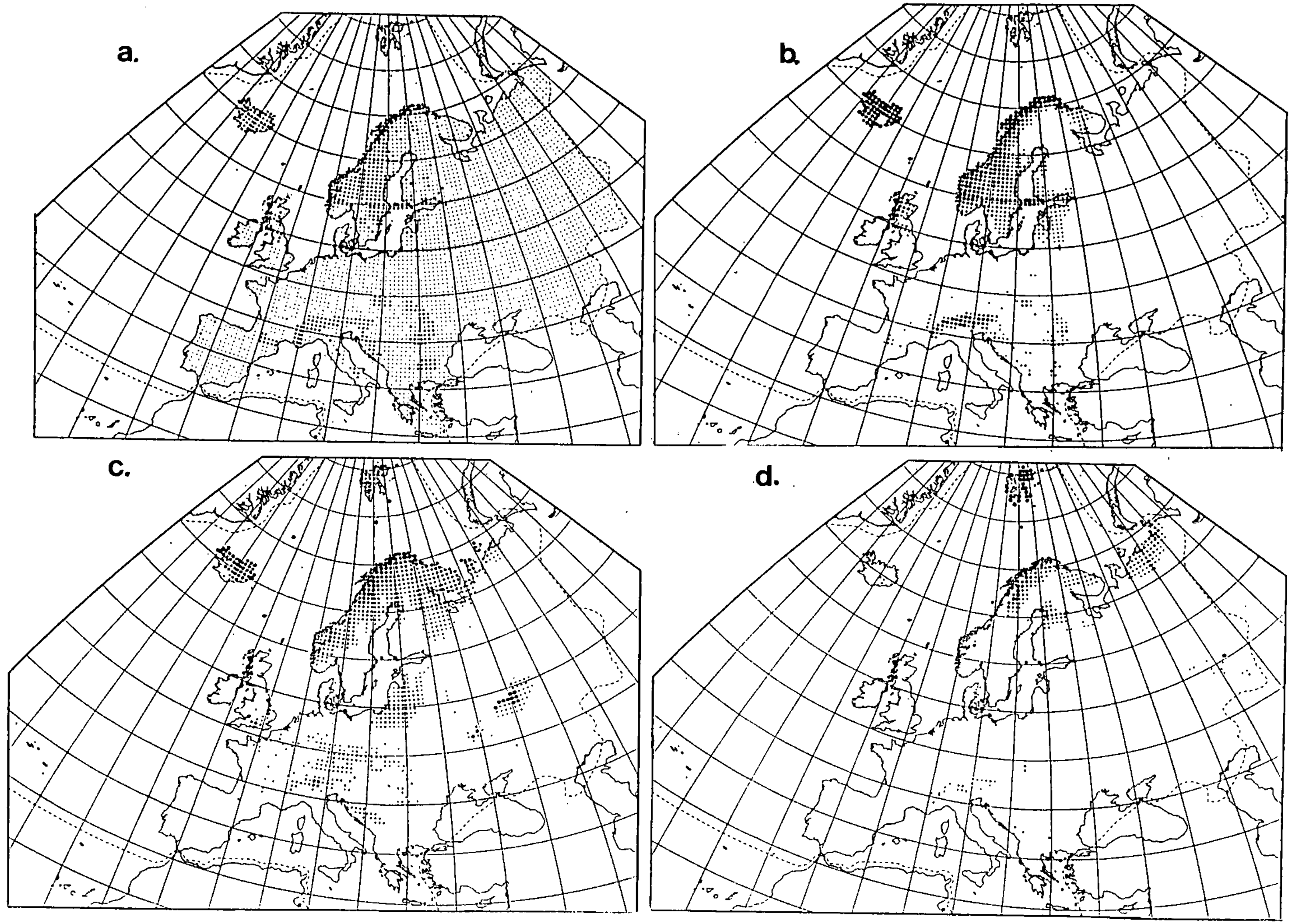
Figure 4.34 ***Potentilla crantzii***

a. AFE distribution

b. Normal simulation threshold probability 0.25

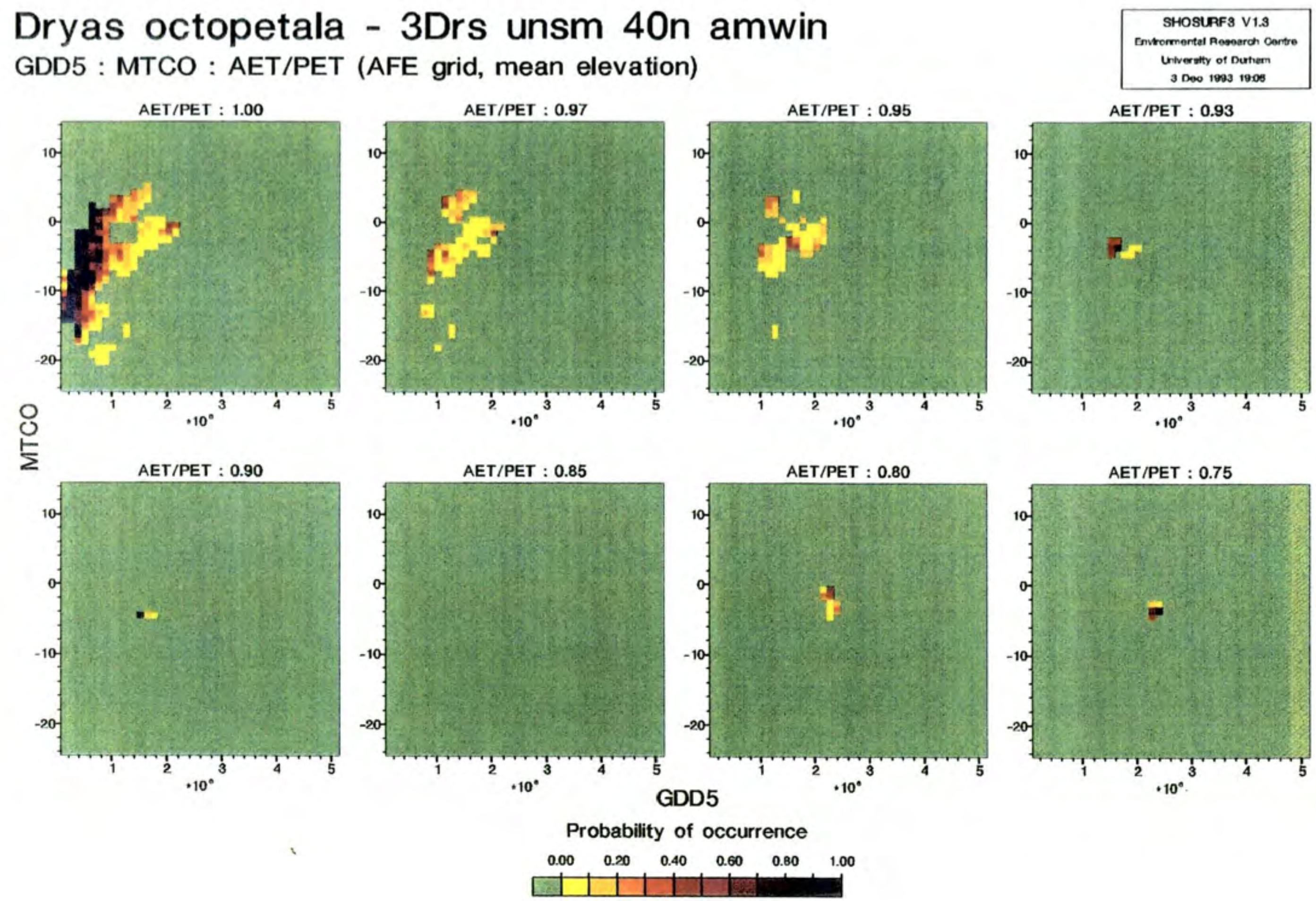
c. OSU simulation

d. UKMO simulation



a.
b.
c.
d.

Figure 4.35



Dryas octopetala - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 19:06
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.36 ***Dryas octopetala***

a. AFE distribution

b. Normal simulation threshold probability 0.15

c. OSU simulation

d. UKMO simulation

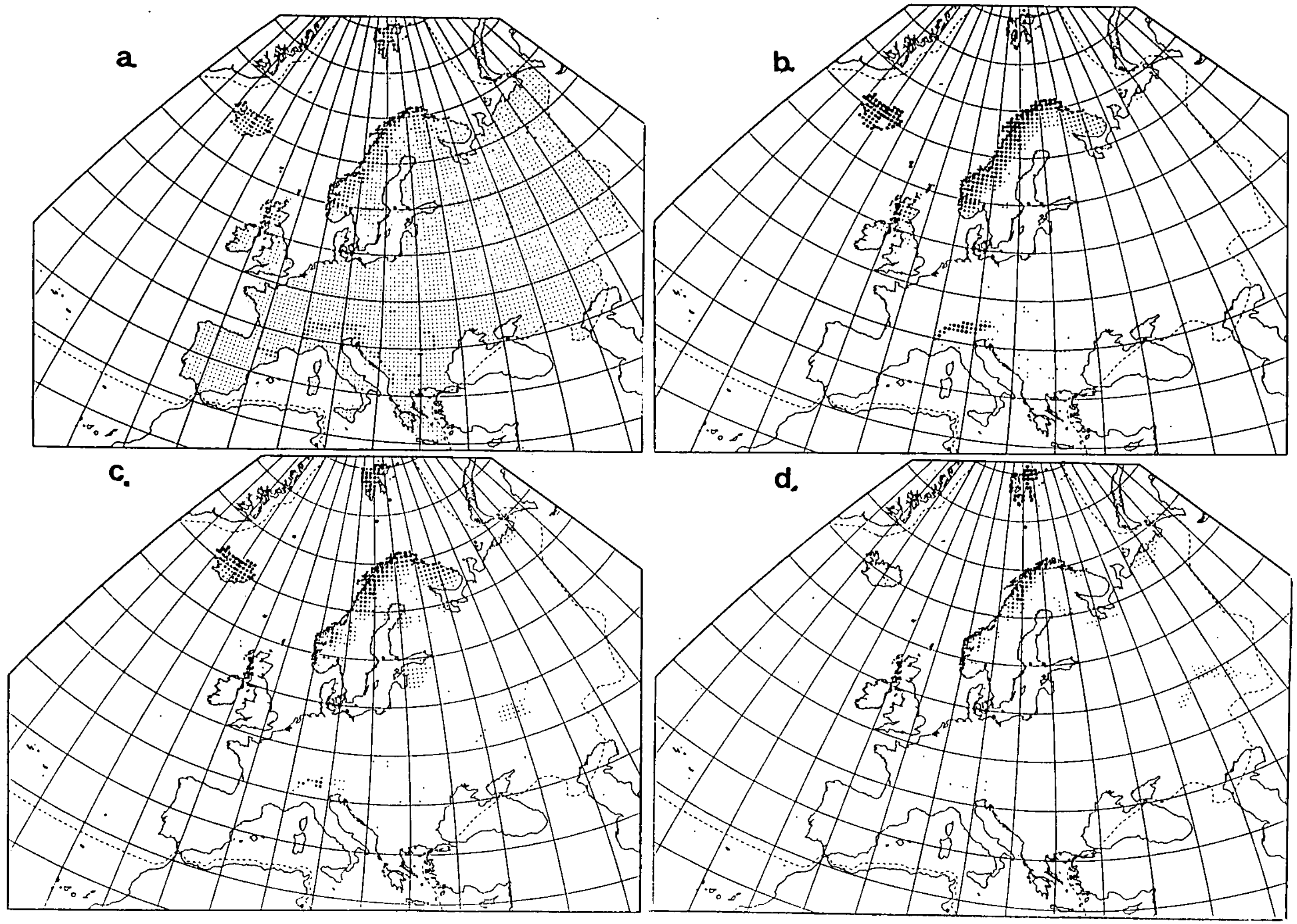

a
b
c
d

Figure 4.37

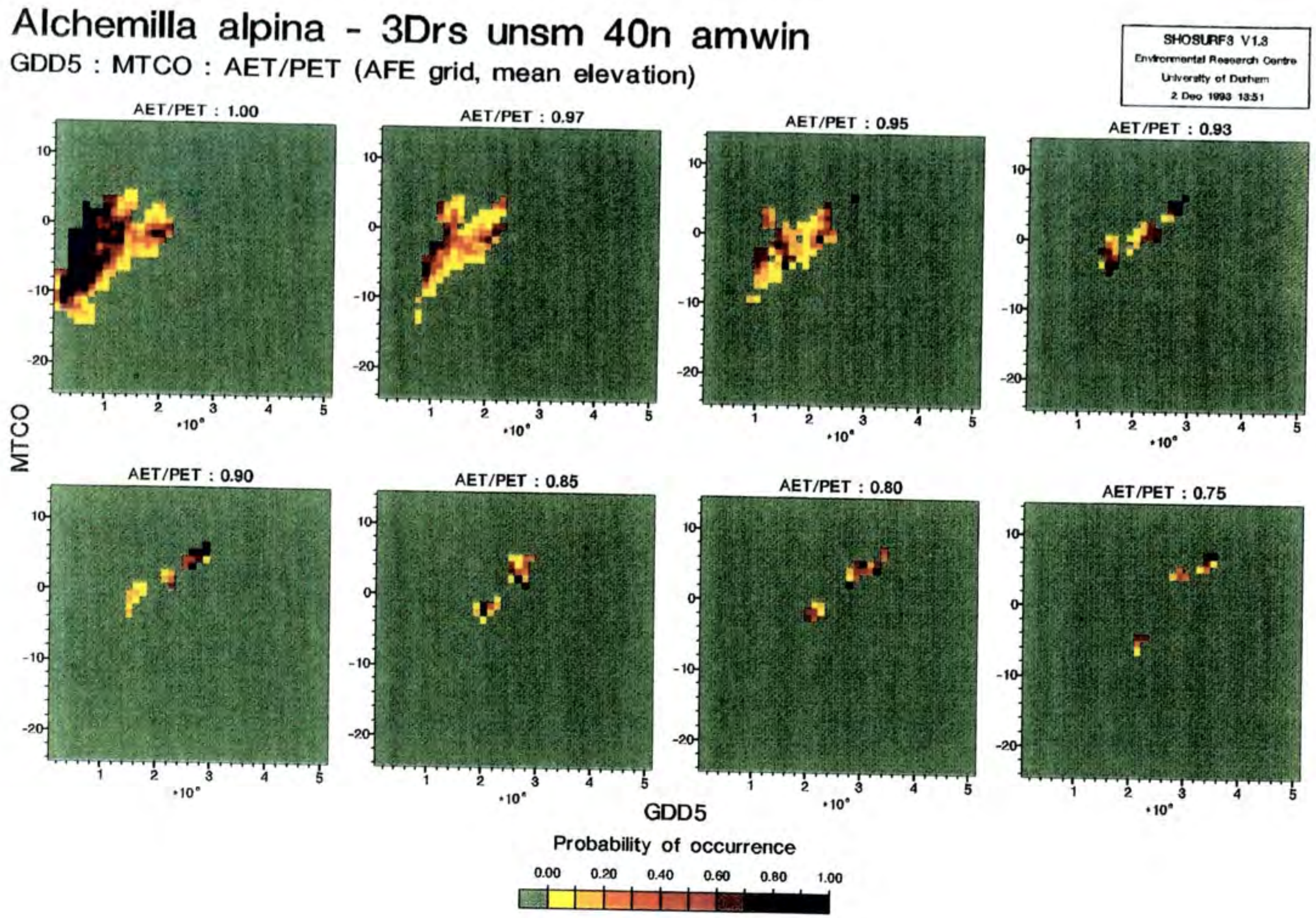

Alchemilla alpina - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
2 Dec 1993 13:51
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

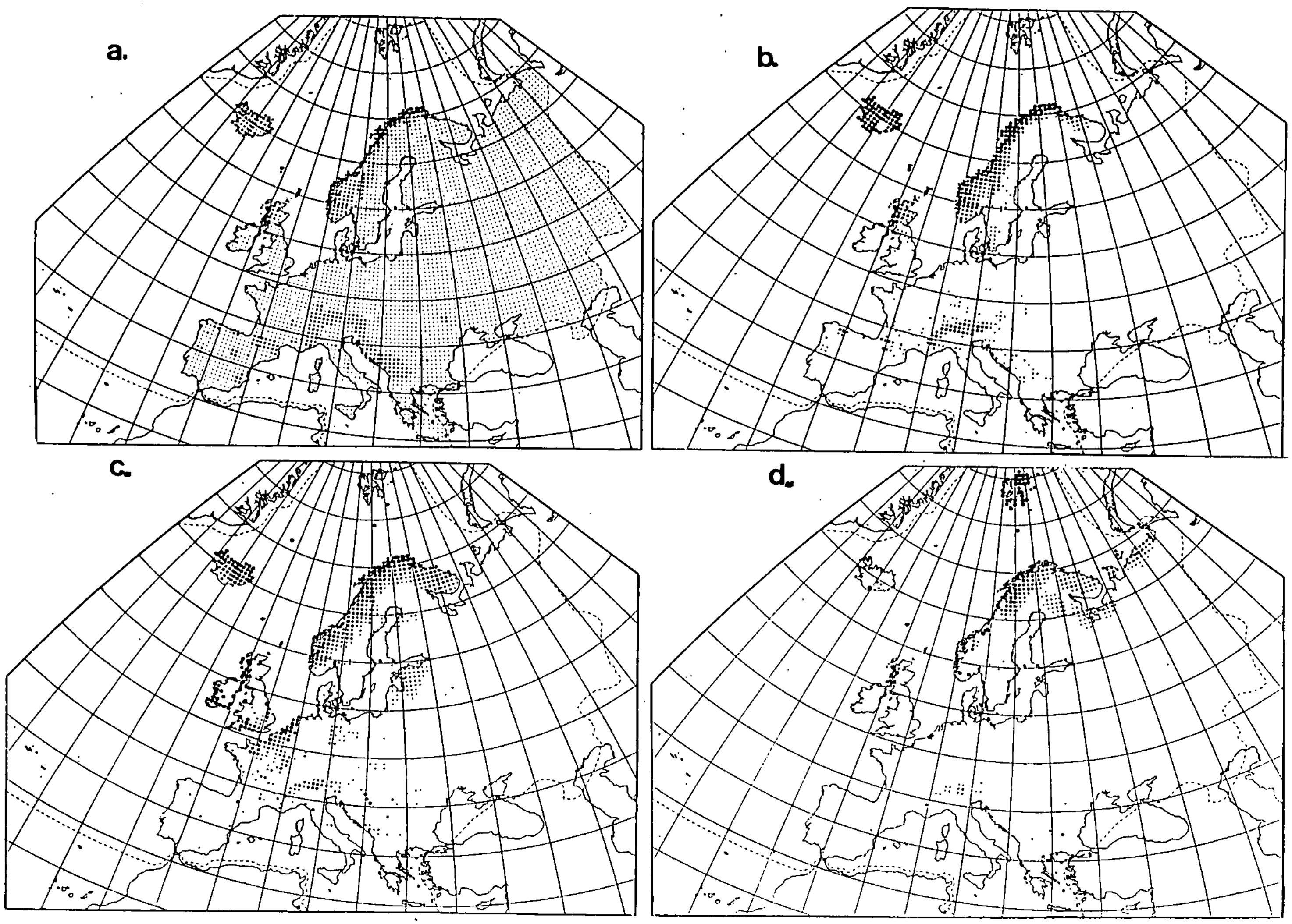
Figure 4.38 ***Alchemilla alpina***

a. AFE distribution

b. Normal simulation threshold probability 0.25

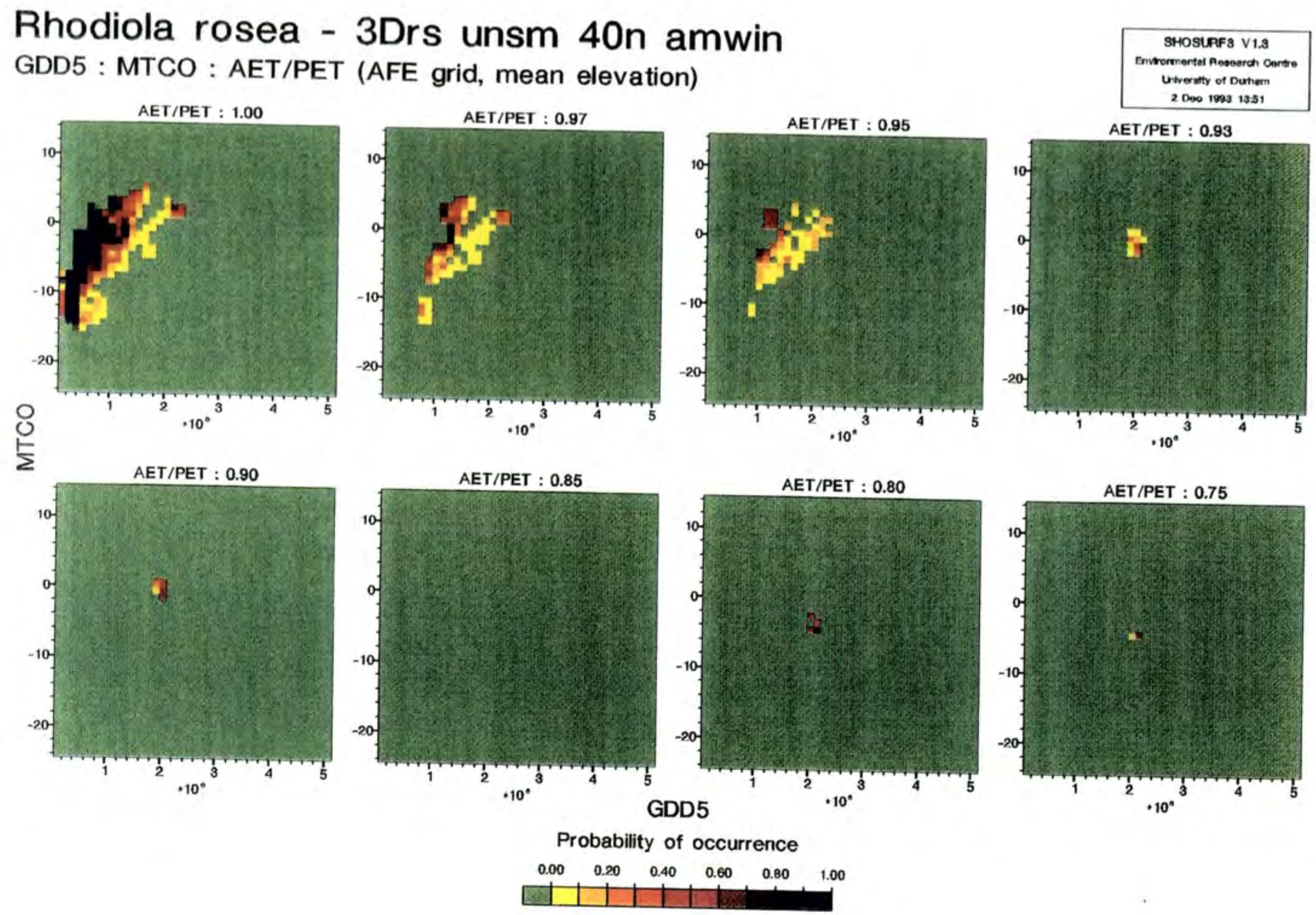
c. OSU simulation

d. UKMO simulation



a.
b.
c.
d.

Figure 4.39



Rhodiola rosea - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
2 Dec 1993 13:51
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.40 ***Rhodiola rosea***

a. AFE distribution

b. Normal simulation threshold probability 0.25

c. OSU simulation

d. UKMO simulation

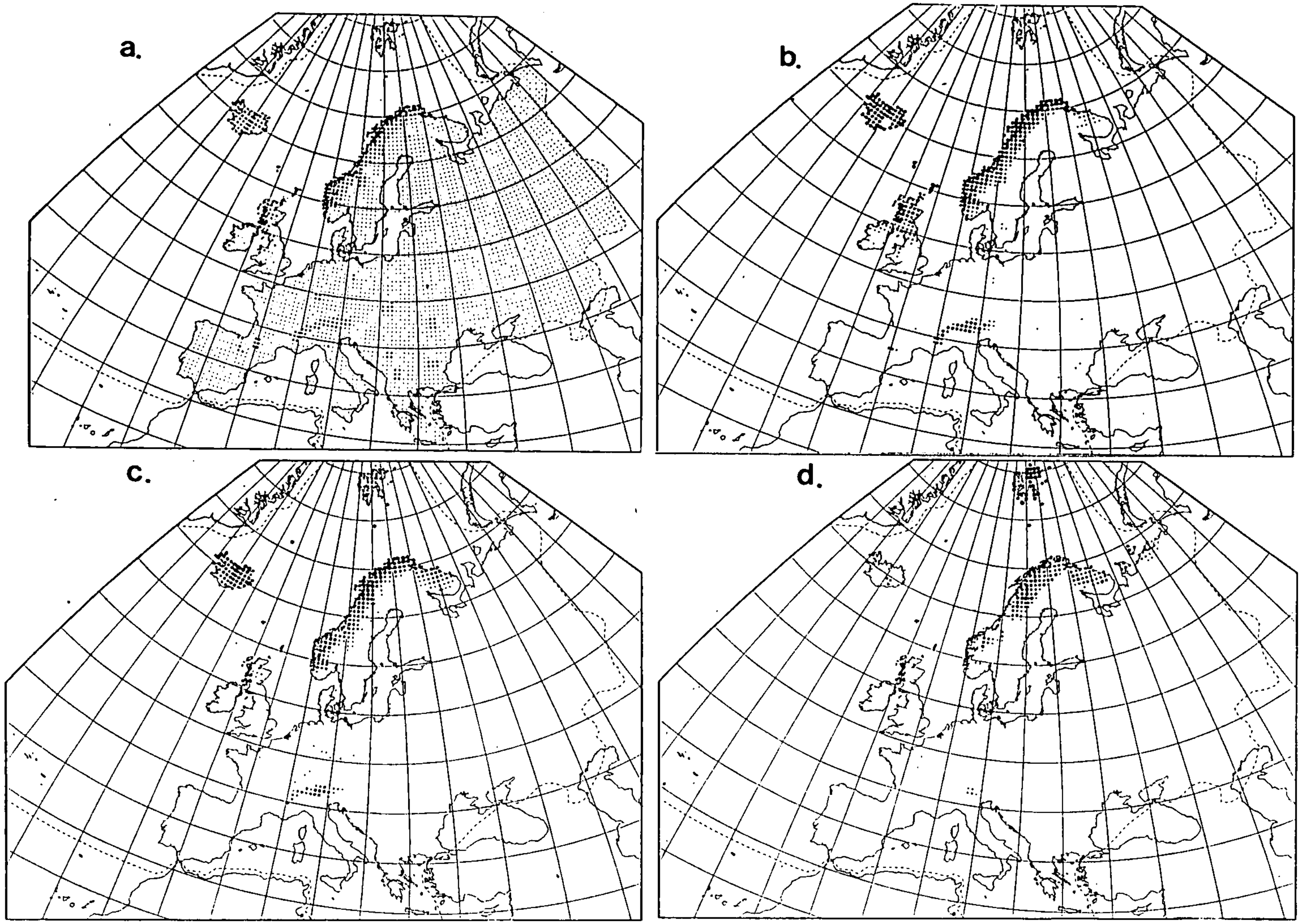

a.
b.
c.
d.

Figure 4.41

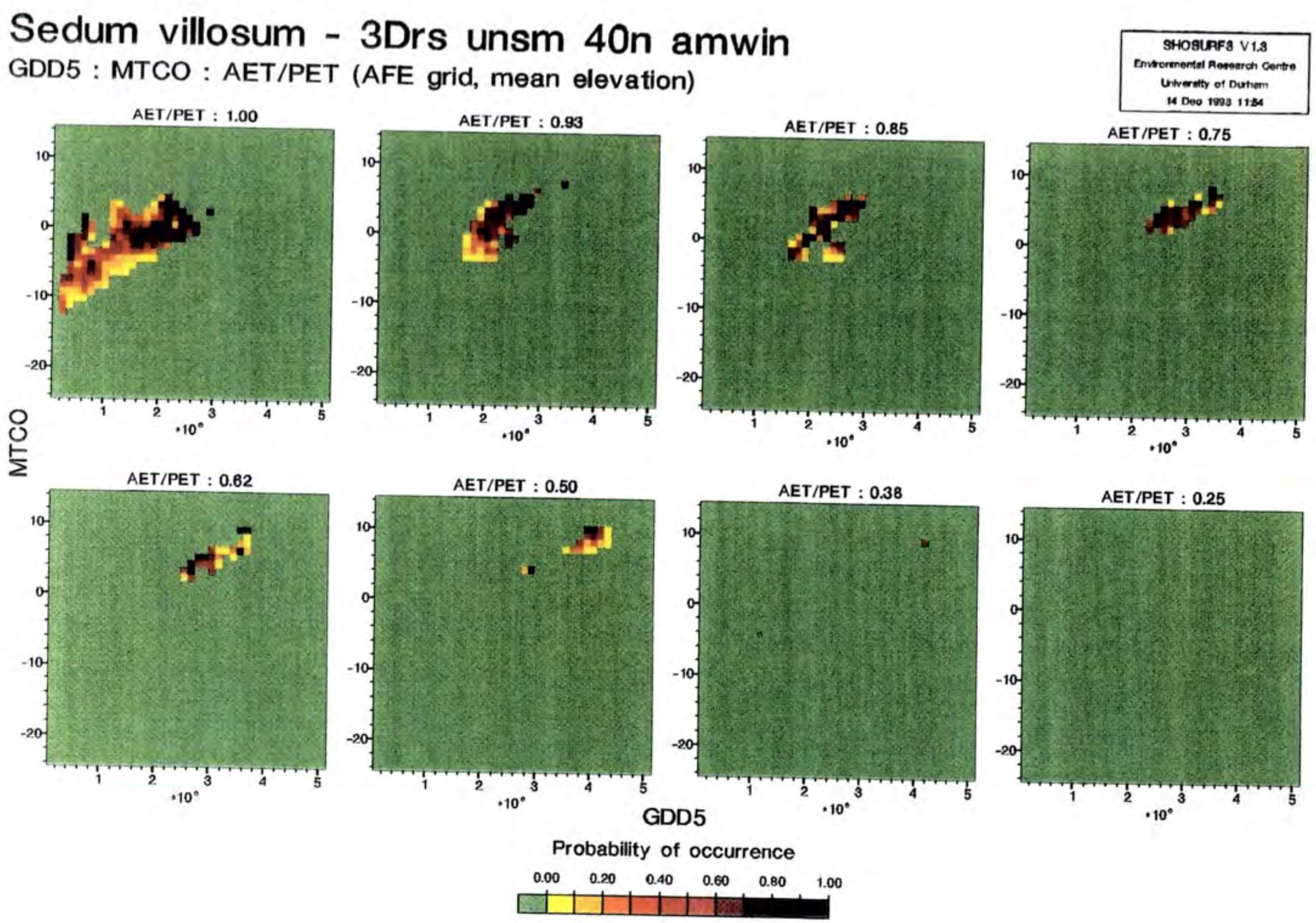

Sedum villosum - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
14 Dec 1993 11:54
AET/PET : 1.00
AET/PET : 0.93
AET/PET : 0.85
AET/PET : 0.75
AET/PET : 0.62
AET/PET : 0.50
AET/PET : 0.38
AET/PET : 0.25
MTCO
GDD5
*10³
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.42 ***Sedum villosum***

a. AFE distribution

b. Normal simulation threshold probability 0.35

c. OSU simulation

d. UKMO simulation

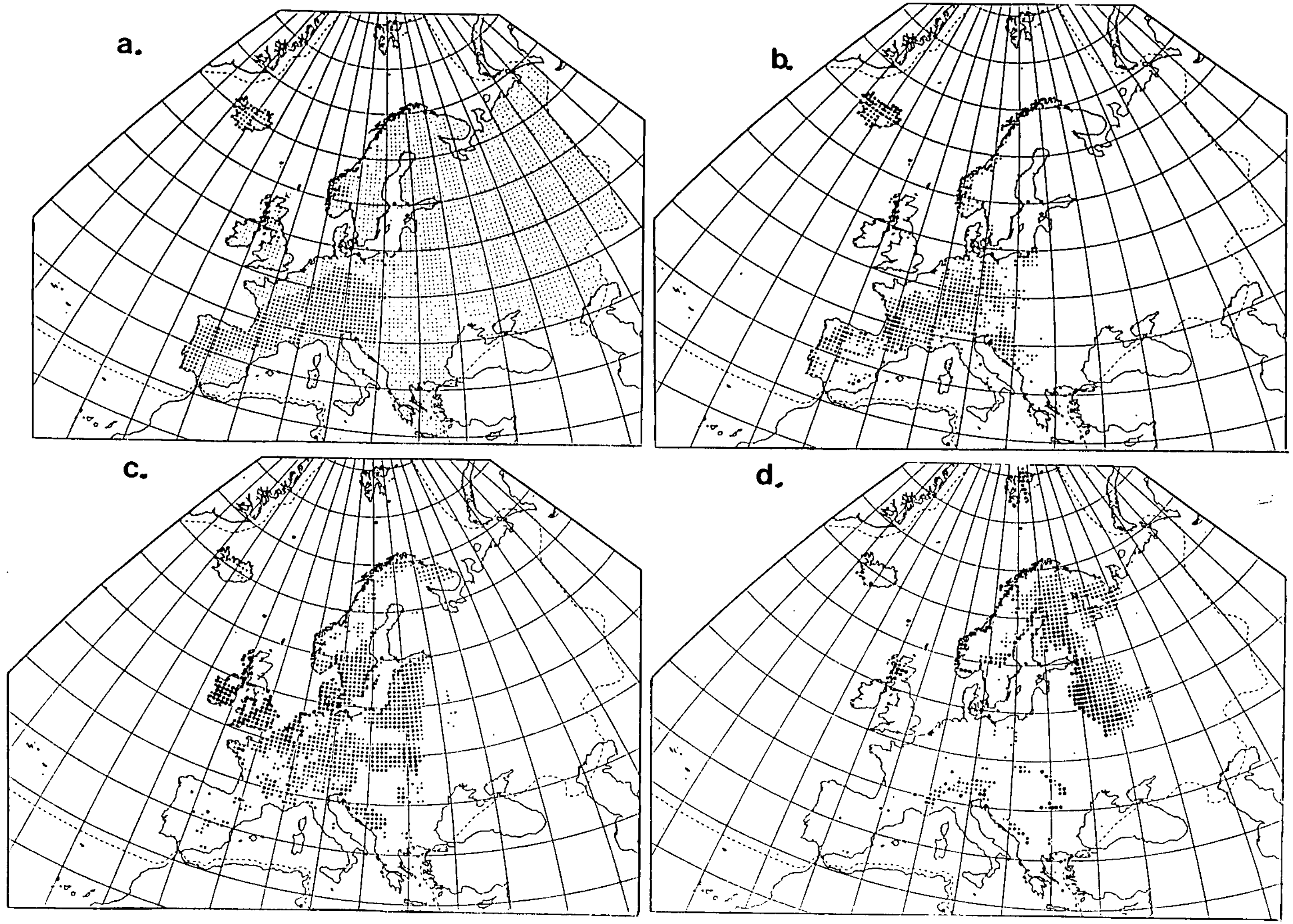

a.
b.
c.
d.

Figure 4.43

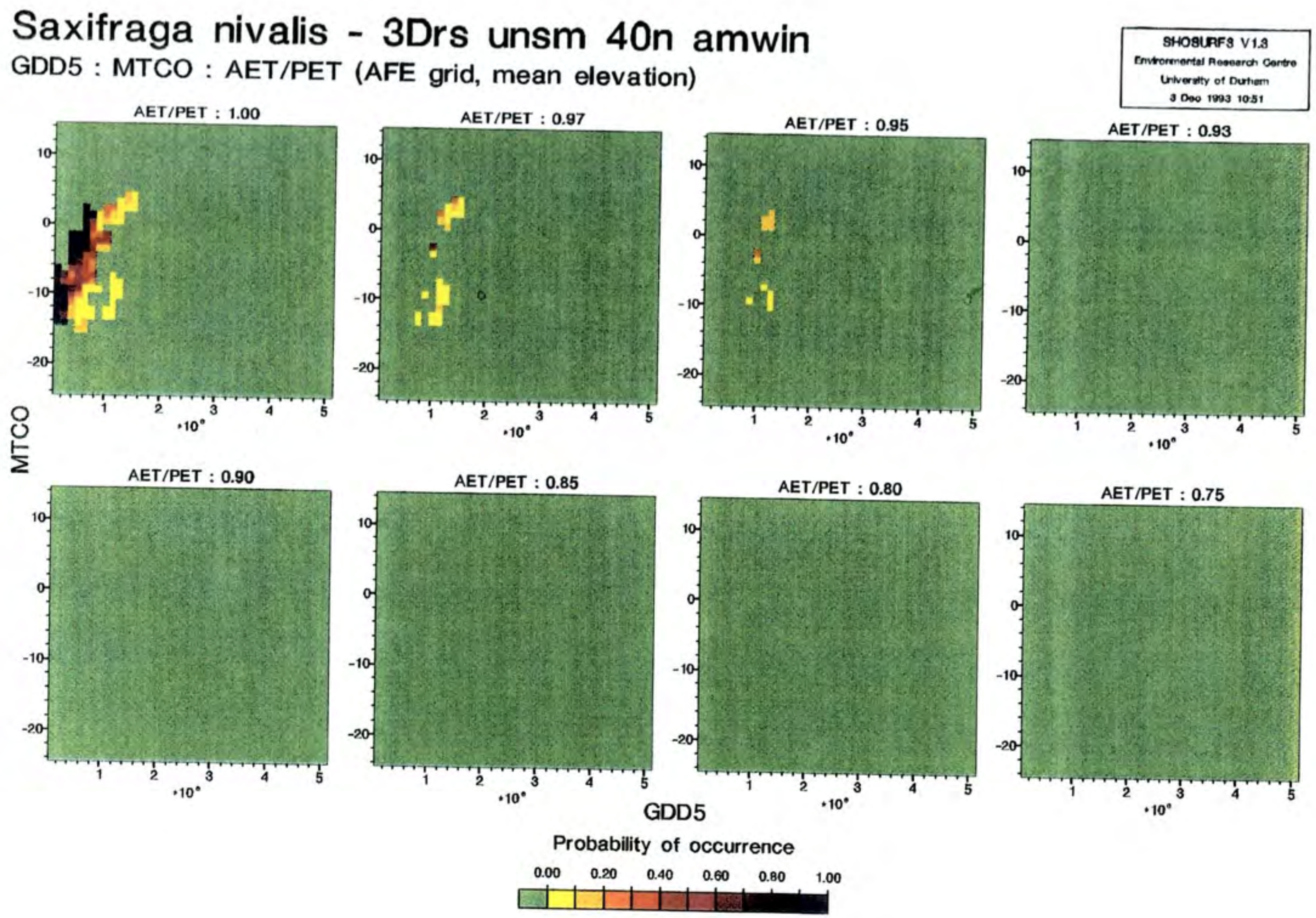

Saxifraga nivalis - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 10:51
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.44 ***Saxifraga nivalis***

a. AFE distribution

b. Normal simulation threshold probability 0.25

c. OSU simulation

d. UKMO simulation

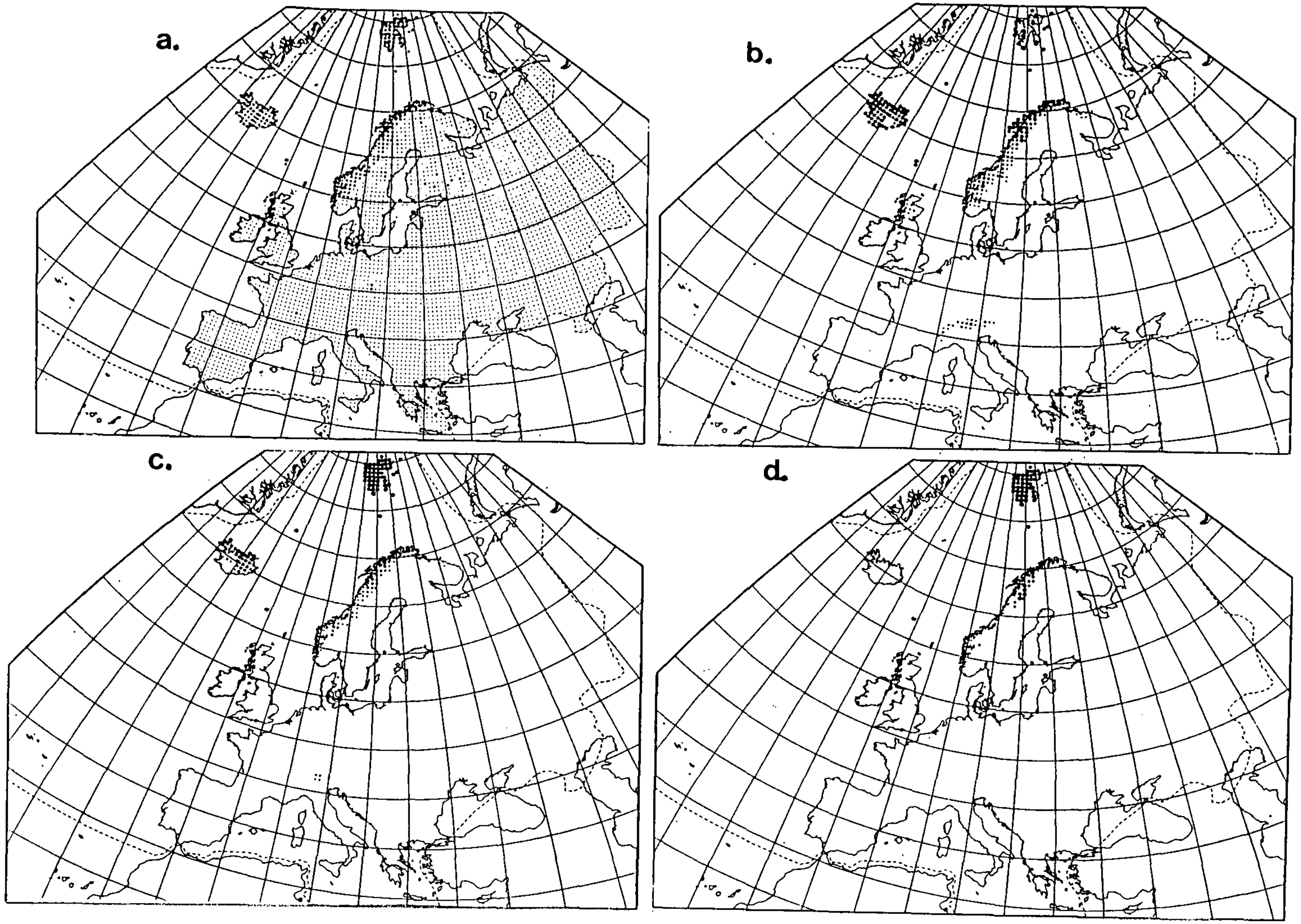
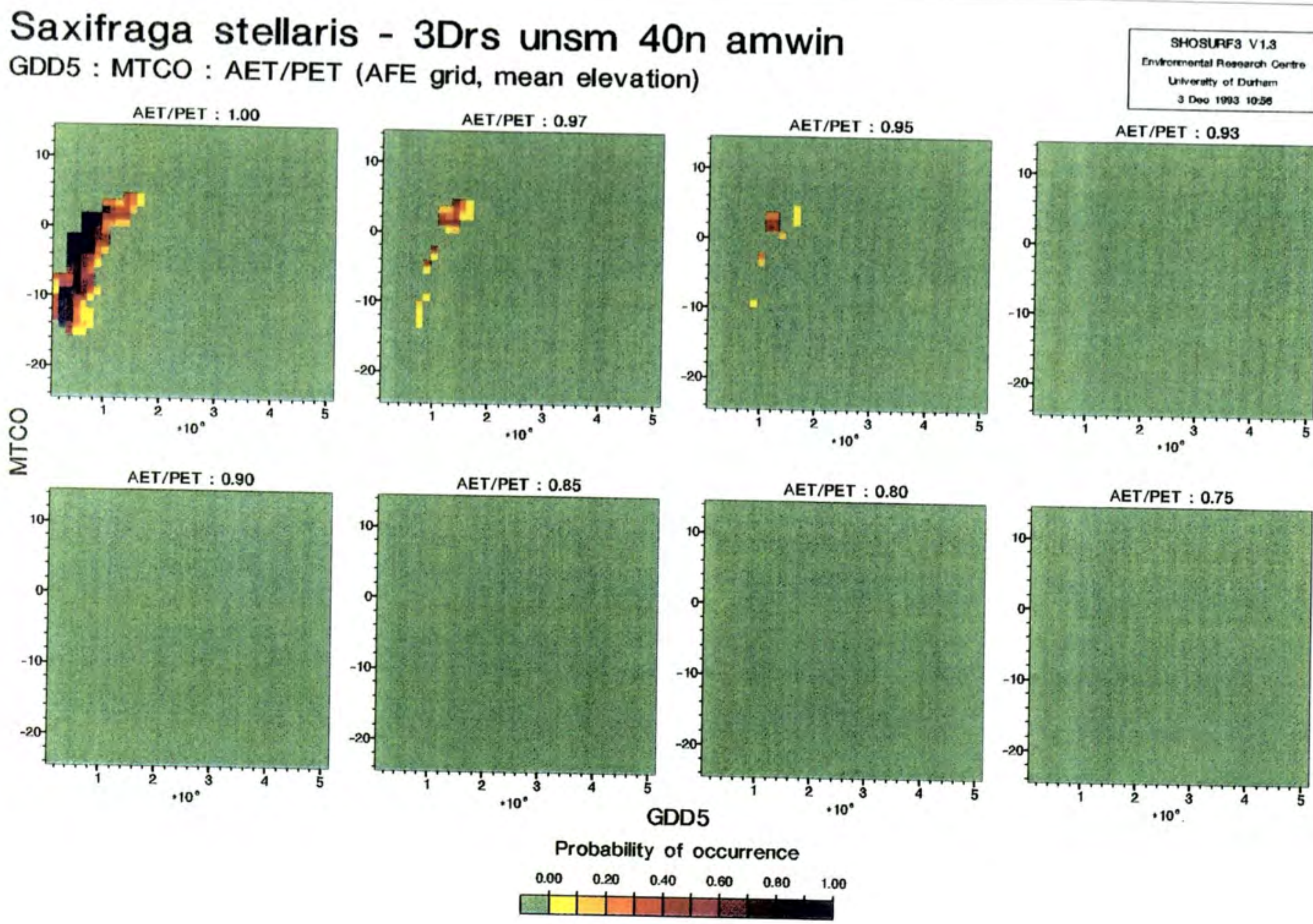

a.
b.
c.
d.

Figure 4.45



Saxifraga stellaris - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 10:56
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.46 ***Saxifraga stellaris***

a. AFE distribution

b. Normal simulation threshold probability 0.35

c. OSU simulation

d. UKMO simulation

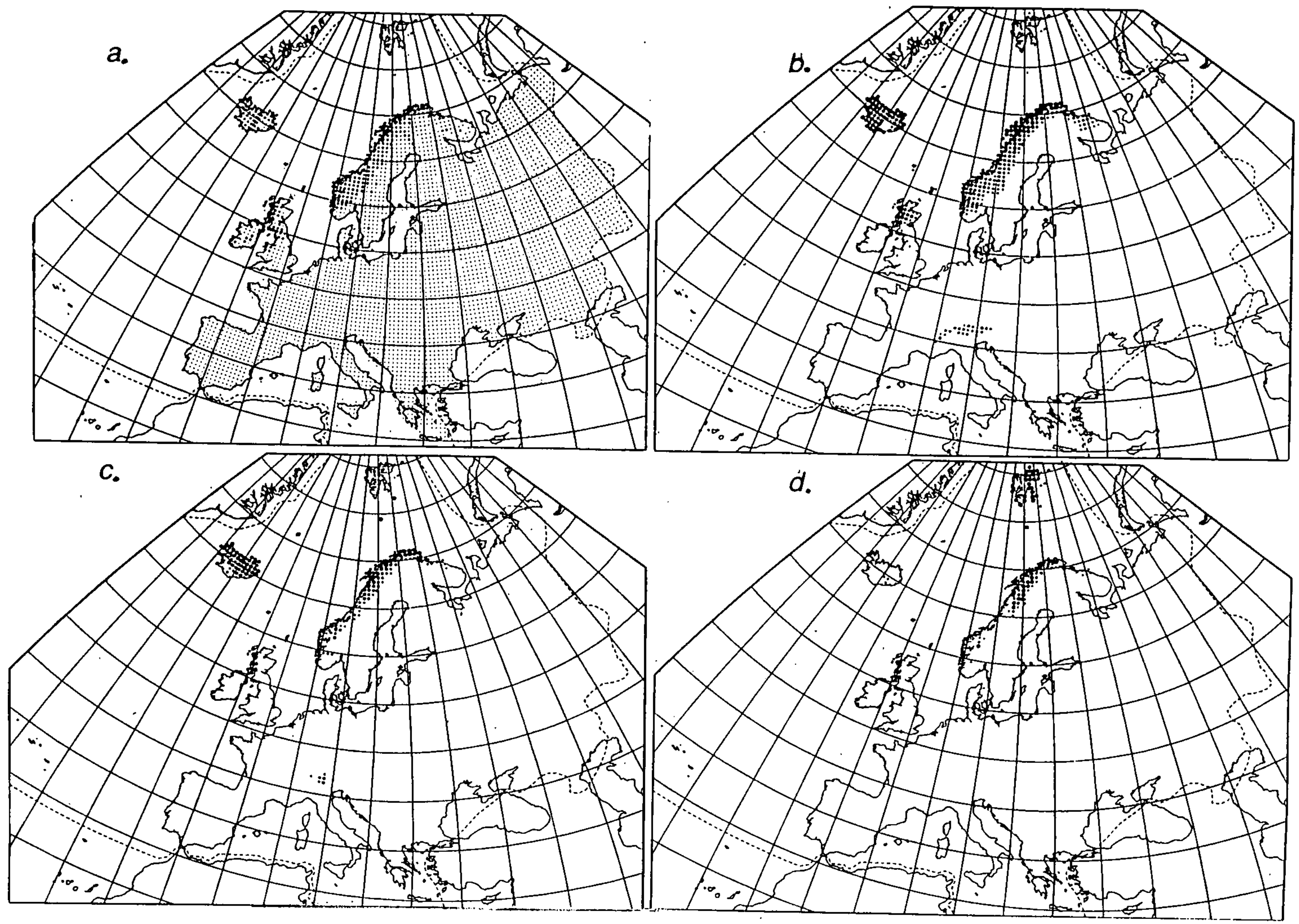
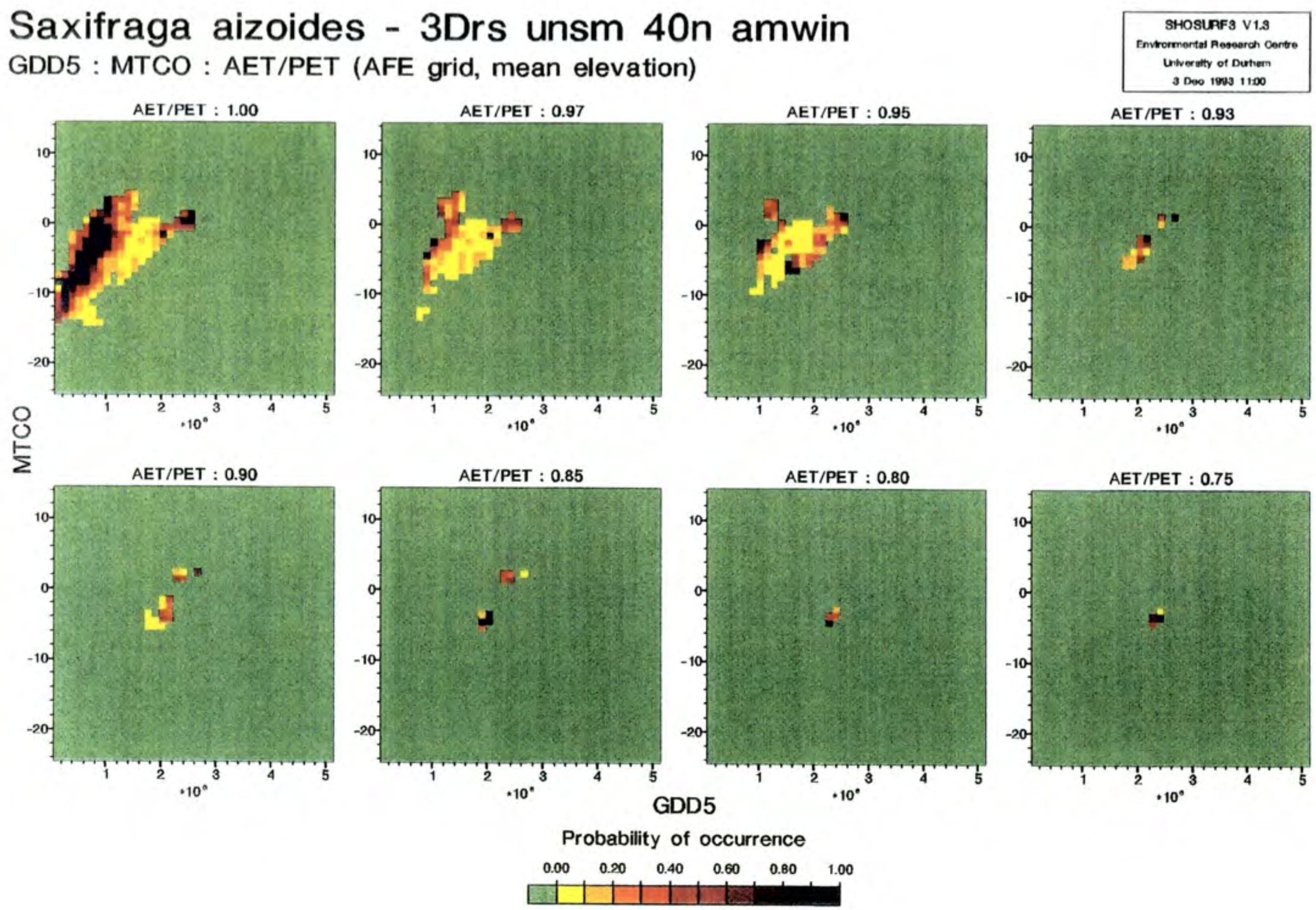

a.
b.
c.
d.

Figure 4.47



Saxifraga aizoides - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 11:00
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.48 ***Saxifraga aizoides***

a. AFE distribution

b. Normal simulation threshold probability 0.25

c. OSU simulation

d. UKMO simulation

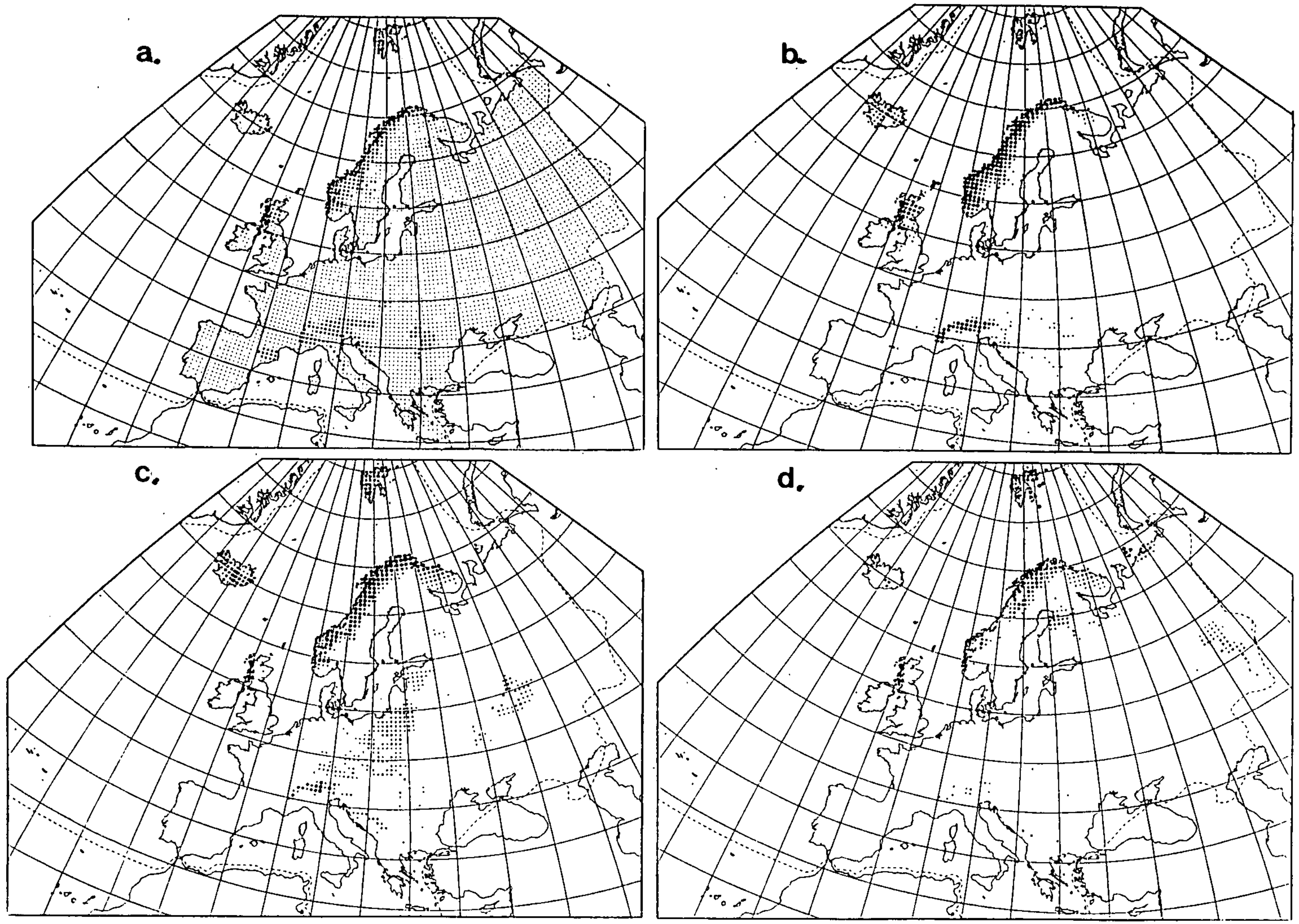
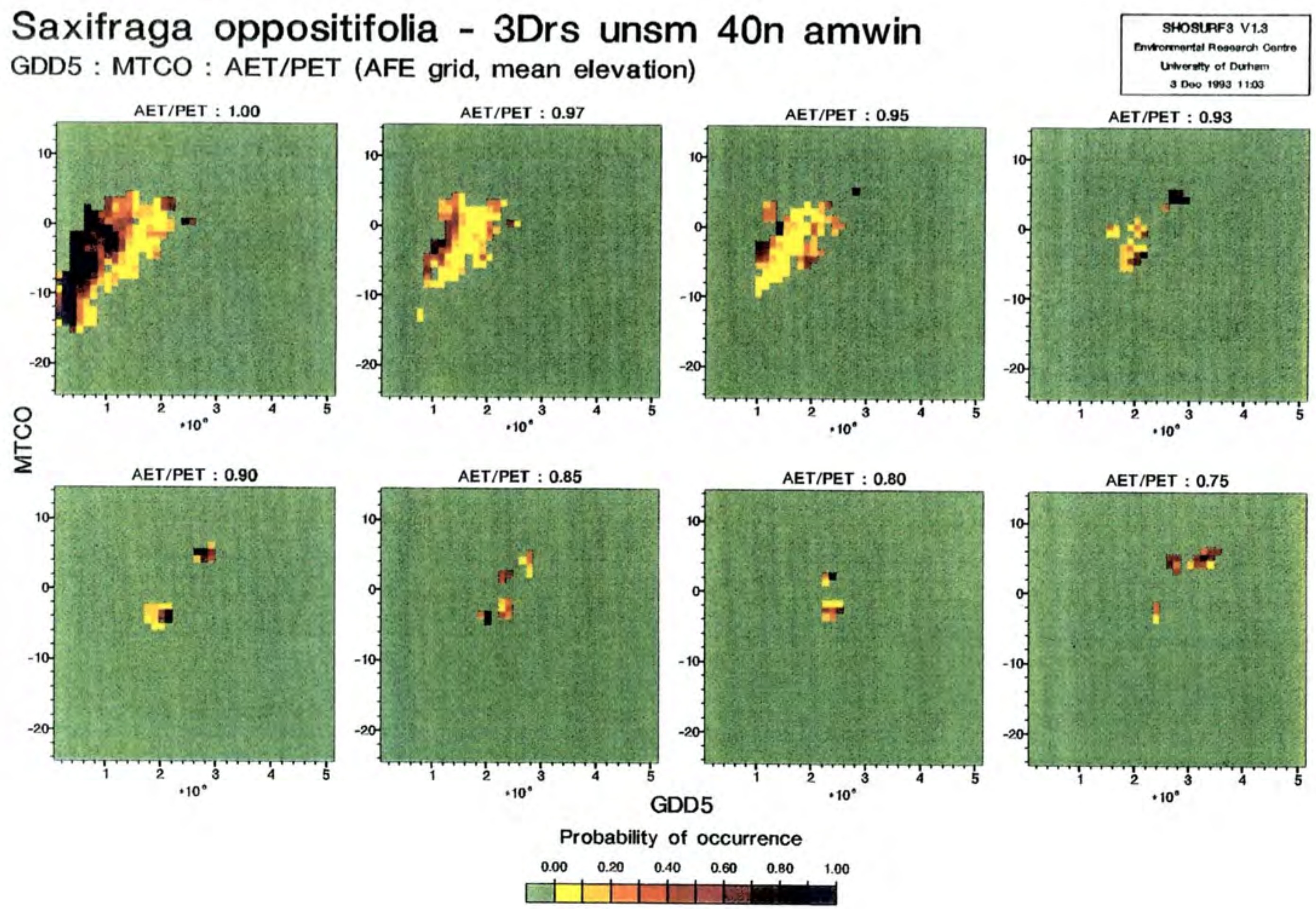

a.
b.
c.
d.

Figure 4.49



Saxifraga oppositifolia - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 11:03
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

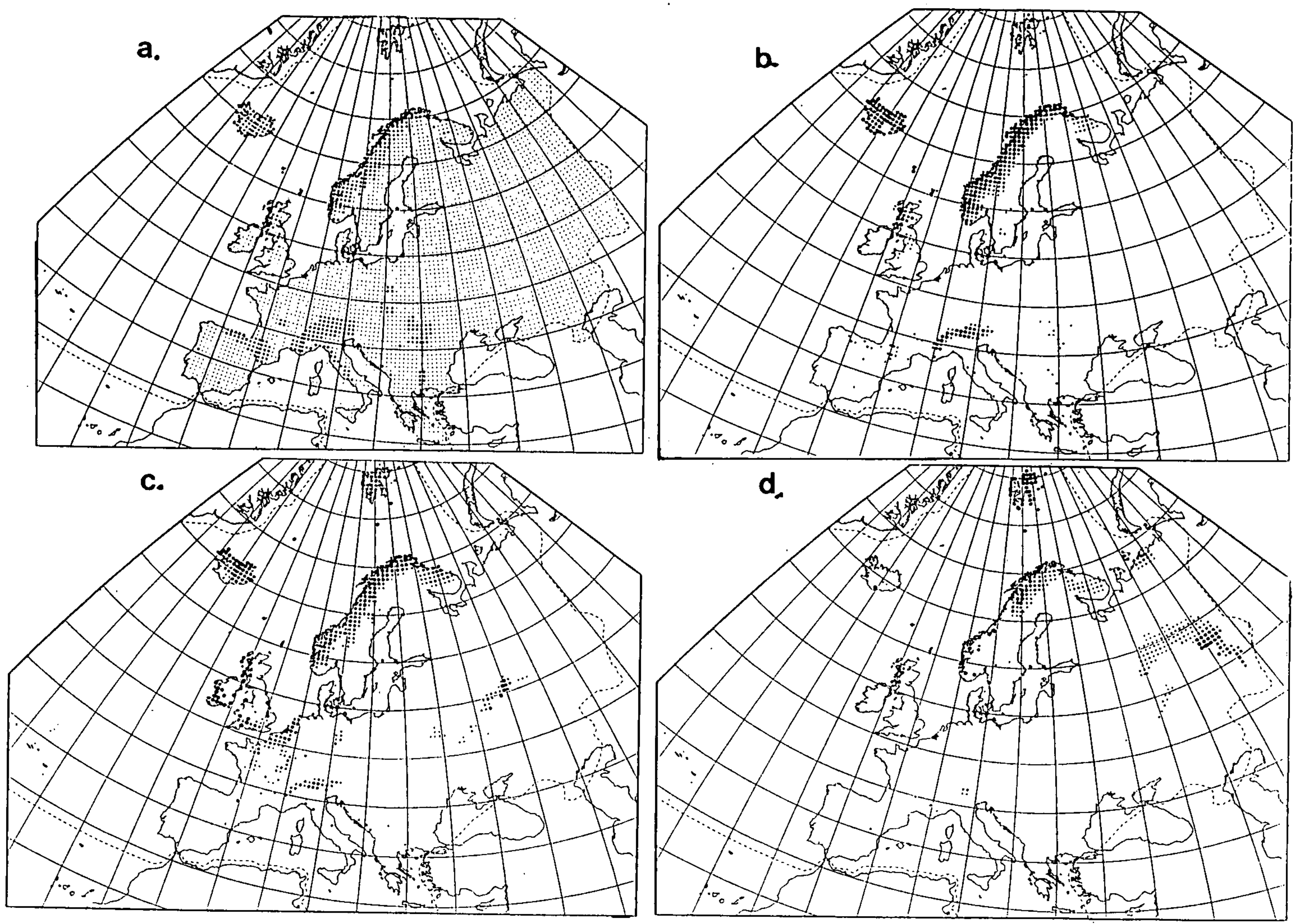
Figure 4.50 ***Saxifraga oppositifolia***

a. AFE distribution

b. Normal simulation threshold probability 0.30

c. OSU simulation

d. UKMO simulation



a.
b.
c.
d.

Figure 4.51

Epilobium anagallidifolium - 3Drs unsm 40n amwin

GDD5 : MTCO : AET/PET (AFE grid, mean elevation)

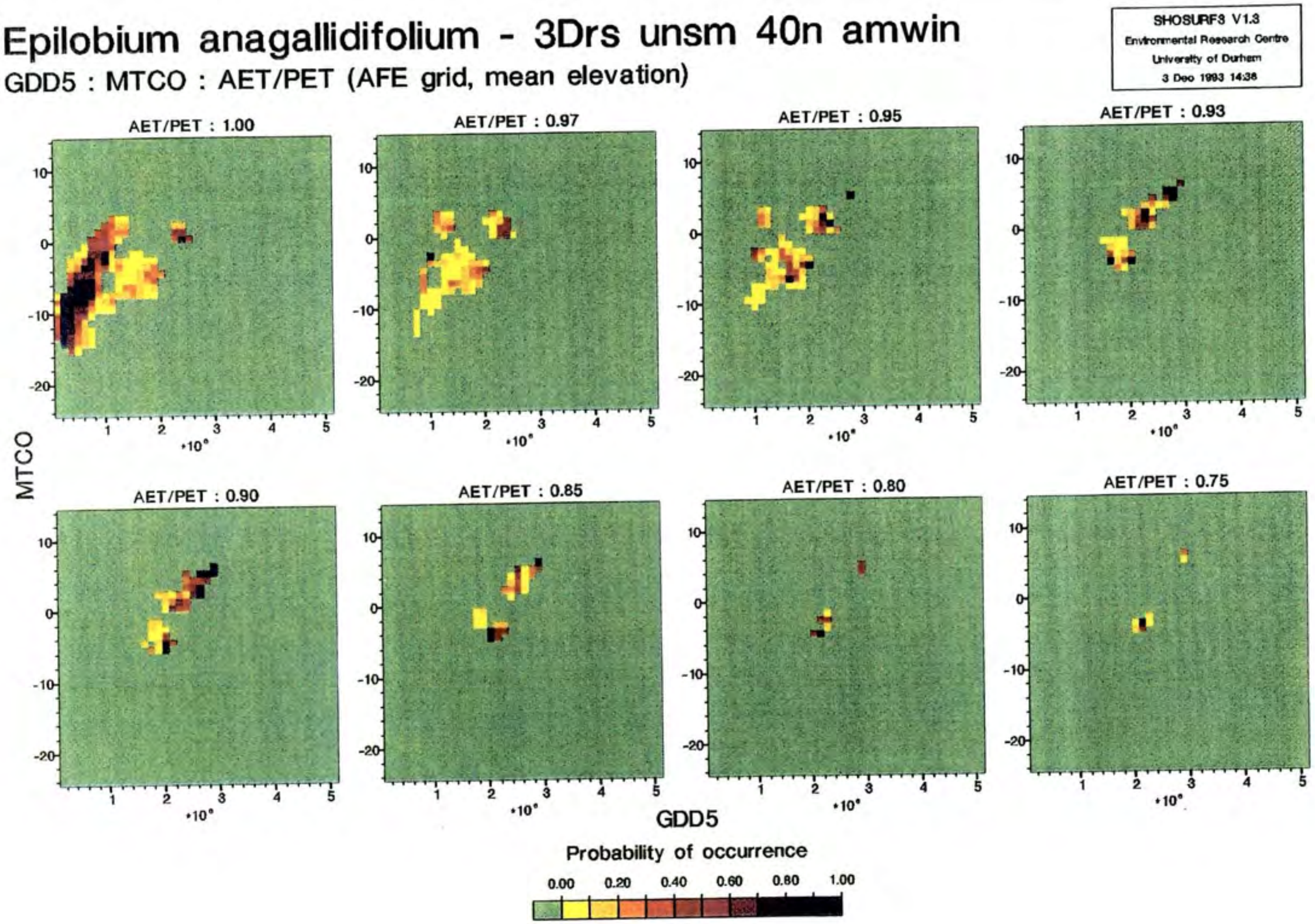


Figure 4.52 ***Epilobium anagallidifolium***

a. AFE distribution

b. Normal simulation threshold probability 0.20

c. OSU simulation

d. UKMO simulation

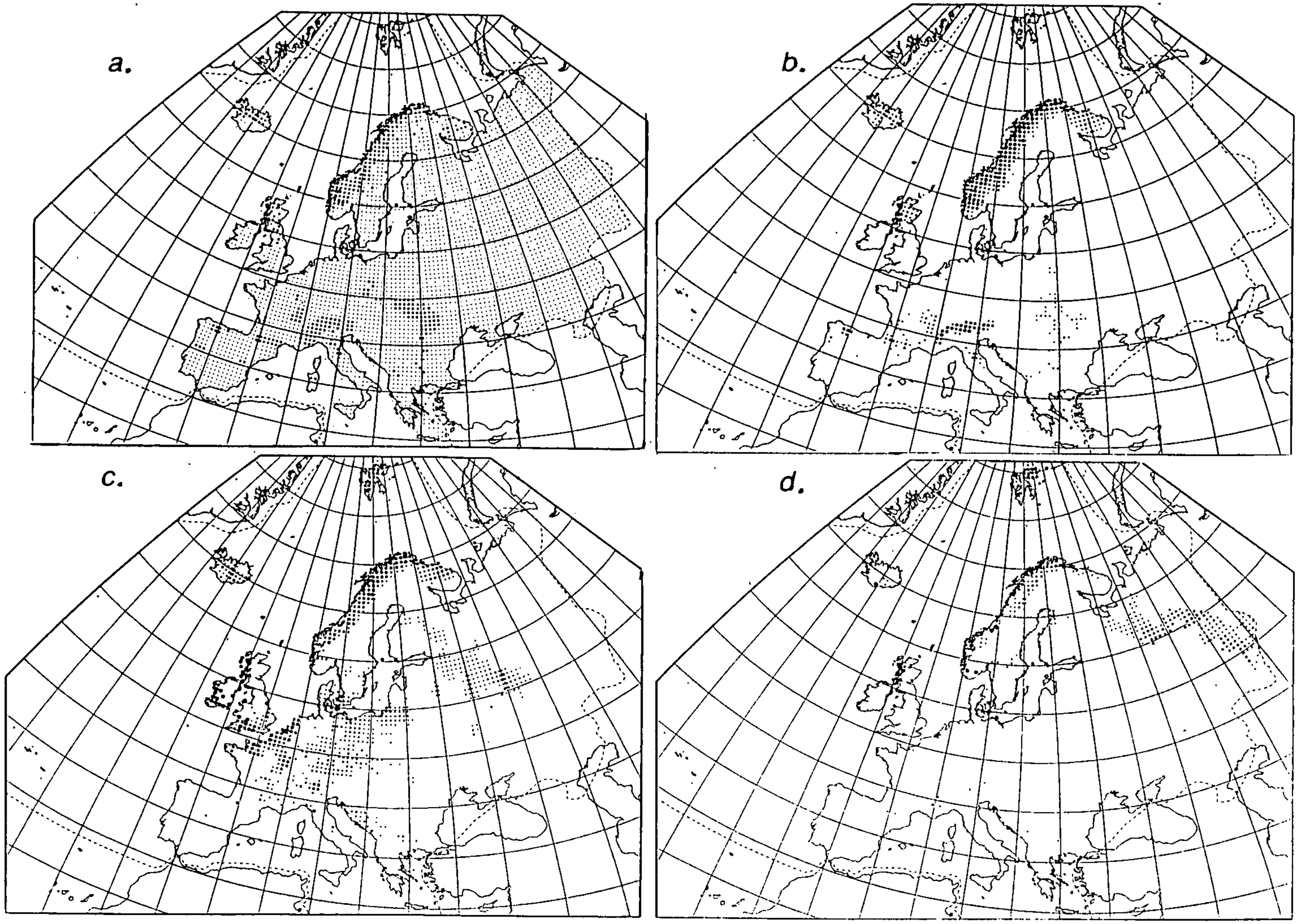

a.
b.
c.
d.

Figure 4.53

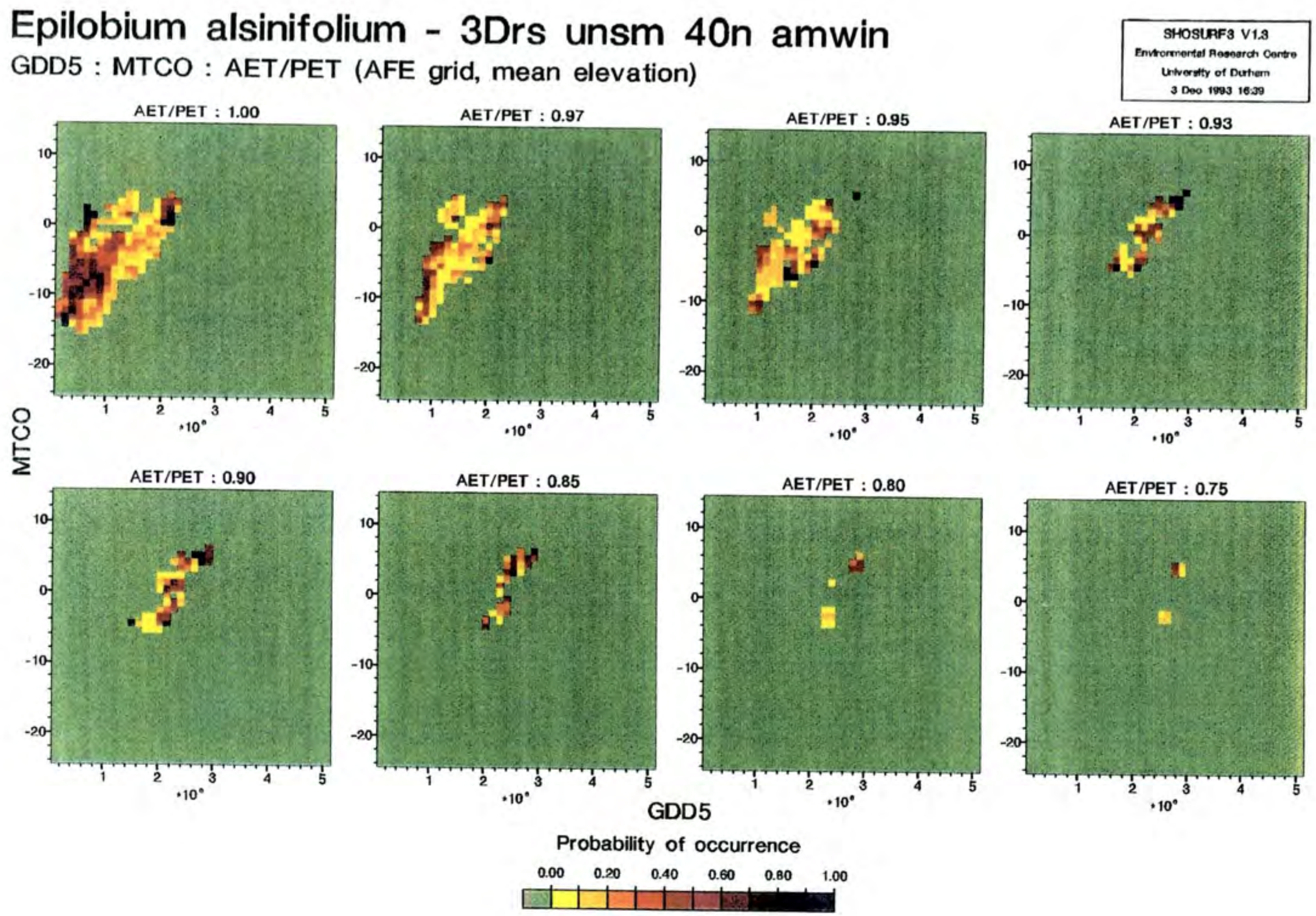

Epilobium alsinifolium - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 16:39
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.54 ***Epilobium alsinifolium***

a. AFE distribution

b. Normal simulation threshold probability 0.25

c. OSU simulation

d. UKMO simulation

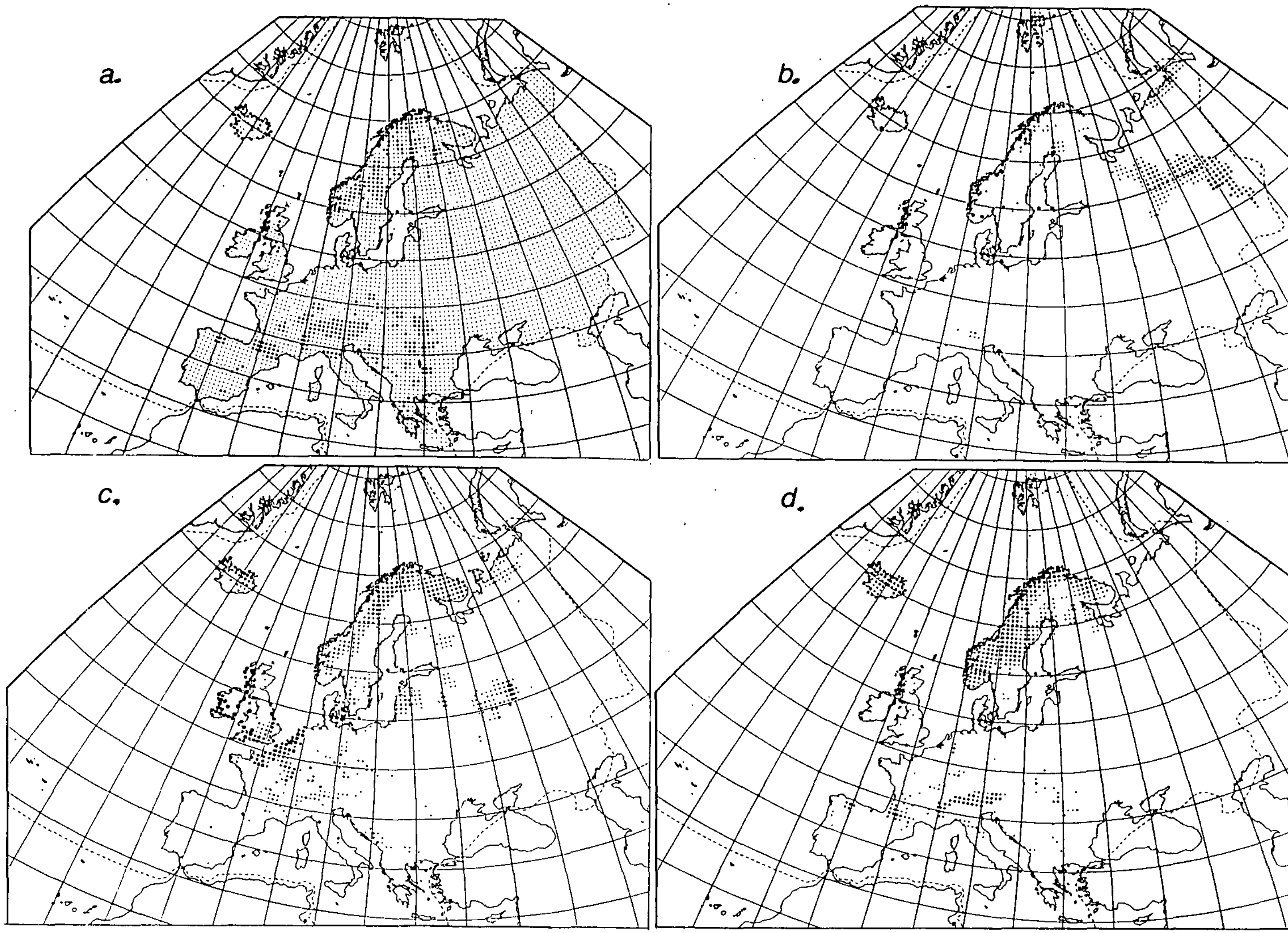
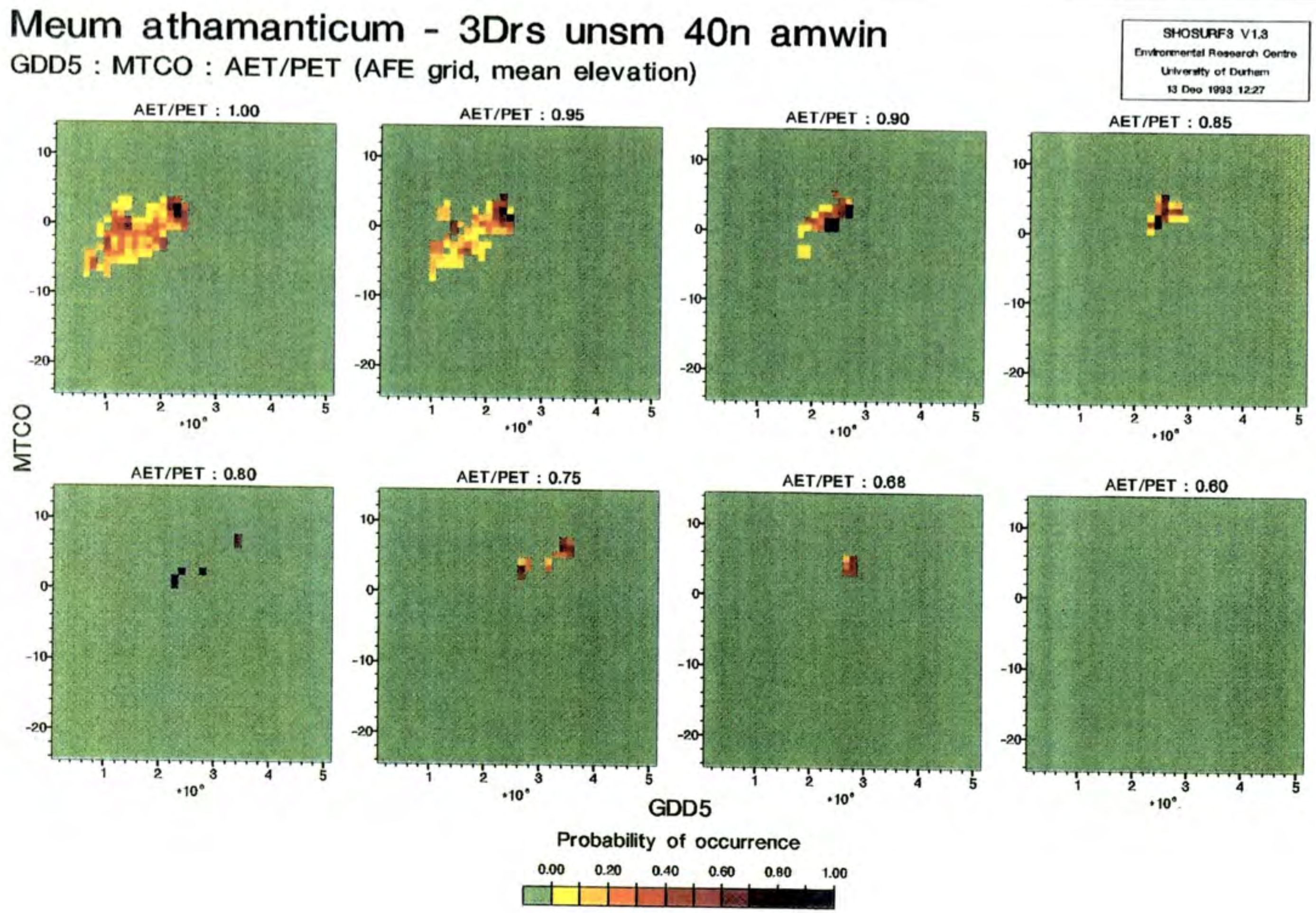

a.
b.
c.
d.

Figure 4.55



Meum athamanticum - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
13 Dec 1993 12:27
AET/PET : 1.00
AET/PET : 0.95
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
AET/PET : 0.68
AET/PET : 0.60
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.56 ***Meum athamanticum***

a. AFE distribution

b. Normal simulation threshold probability 0.20

c. OSU simulation

d. UKMO simulation

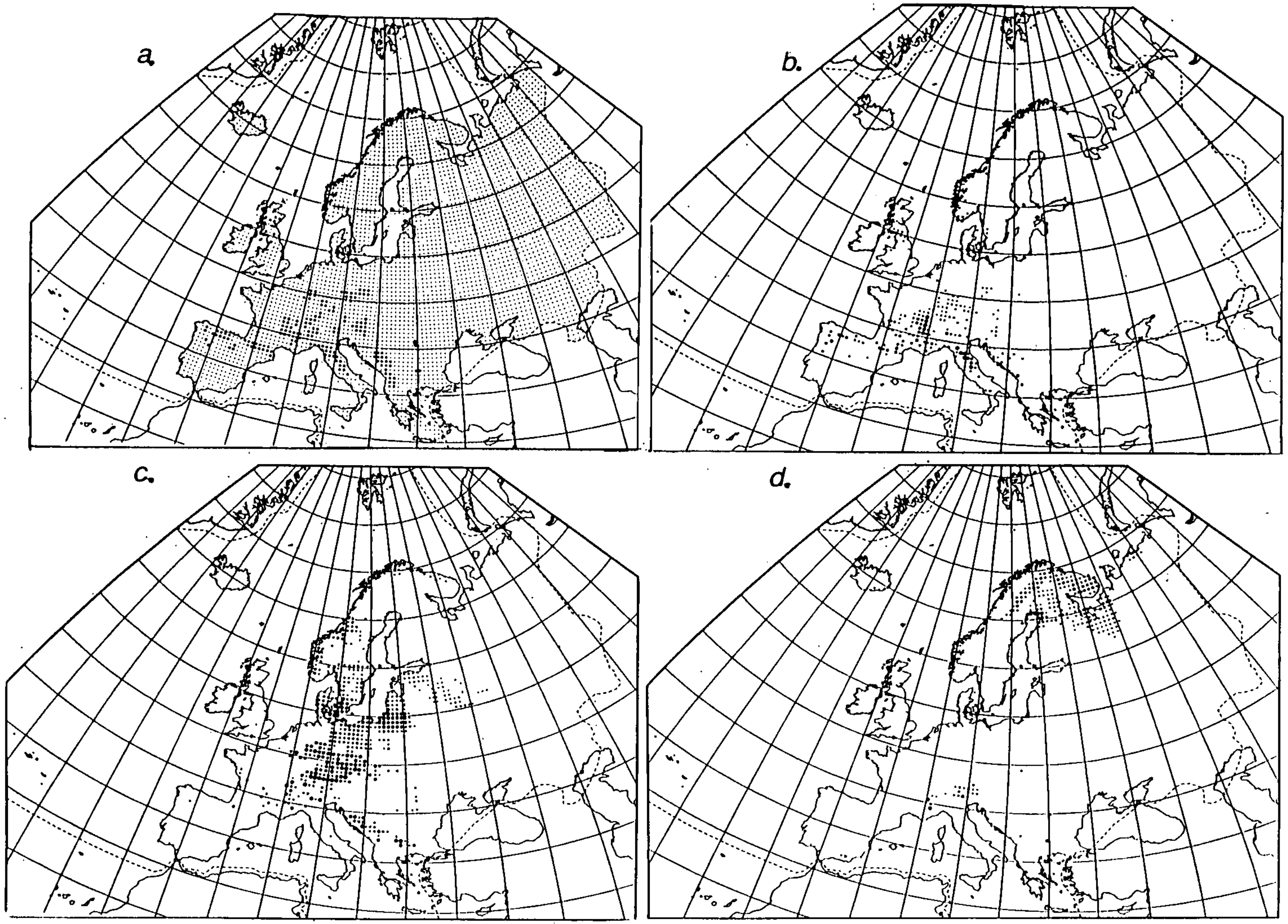
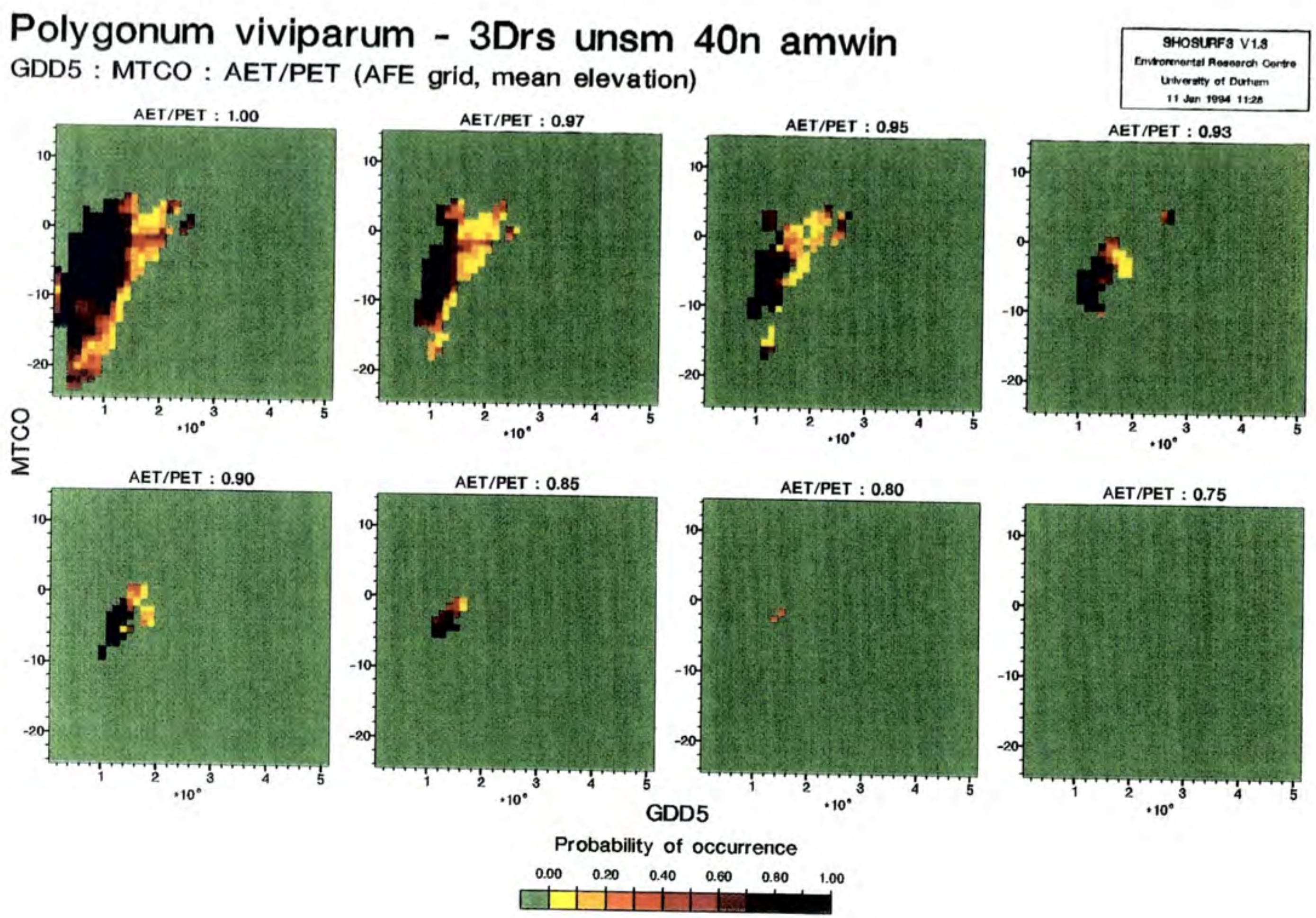

a.
b.
c.
d.

Figure 4.57



Polygonum viviparum - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.8
Environmental Research Centre
University of Durham
11 Jan 1994 11:28
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10³
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.58 ***Polygonum viviparum***

a. AFE distribution

b. Normal simulation threshold probability 0.35

c. OSU simulation

d. UKMO simulation

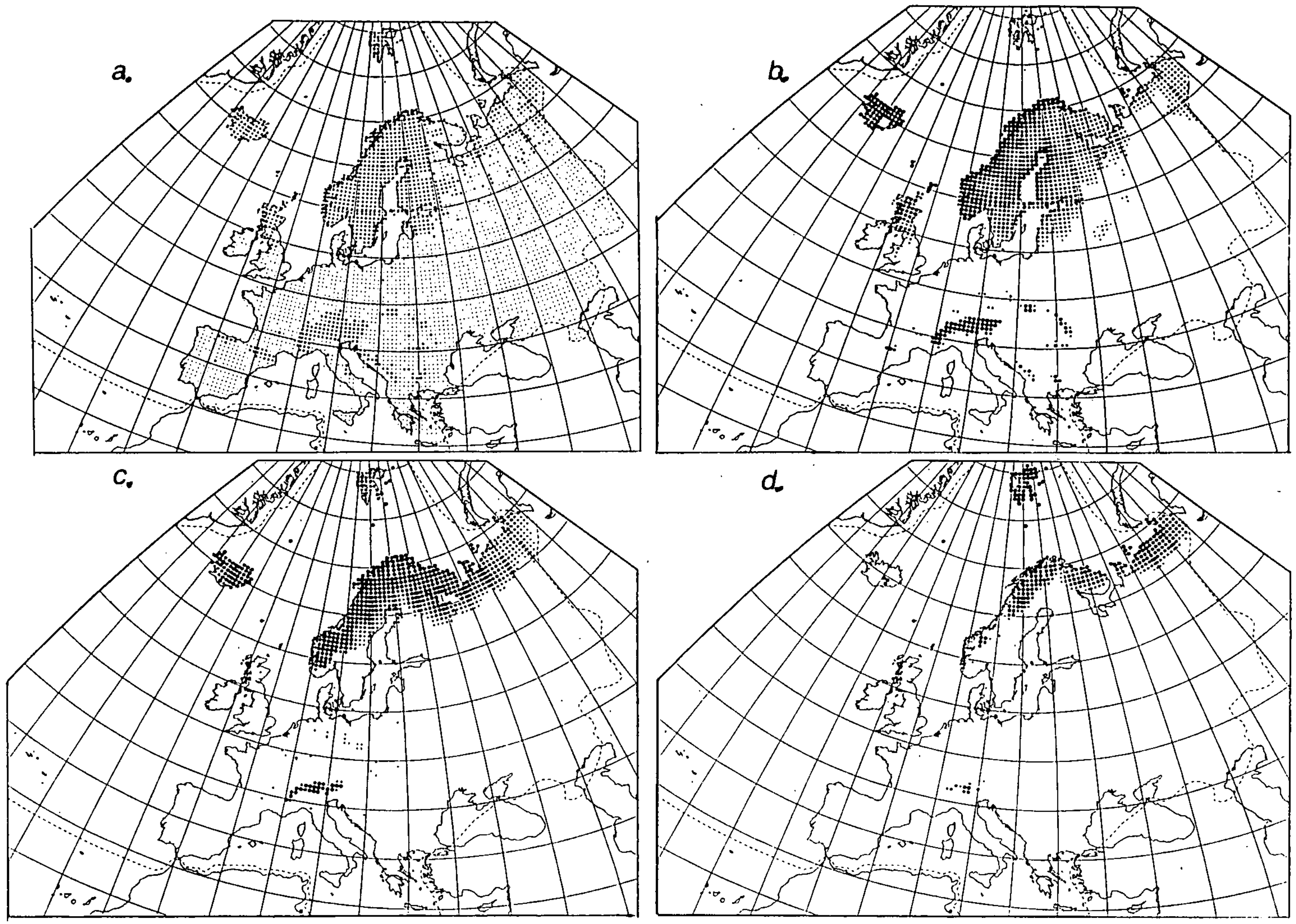
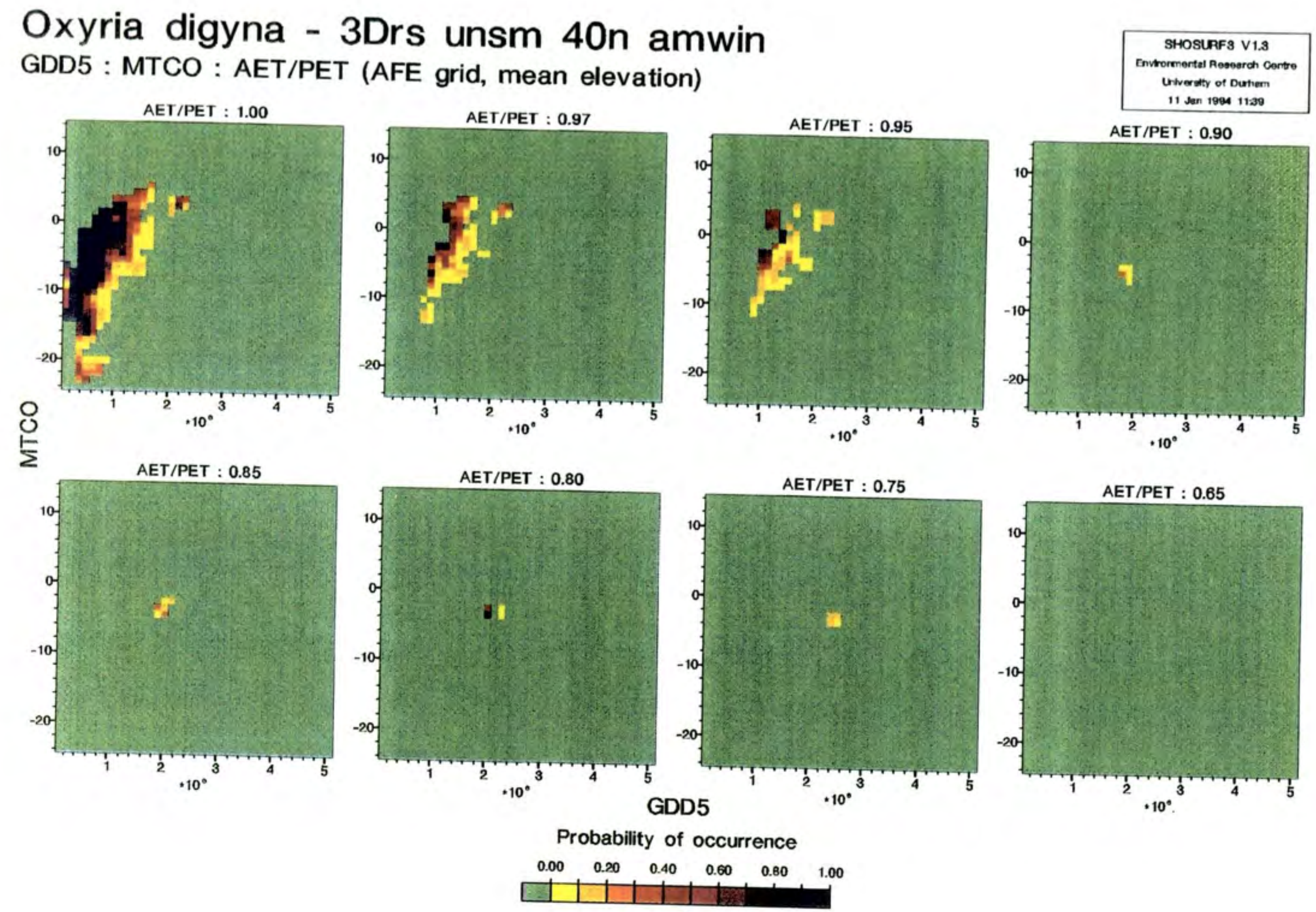

a.
b.
c.
d.

Figure 4.59



Oxyria digyna - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
11 Jan 1994 11:39
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AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
AET/PET : 0.65
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.60 ***Oxyria digyna***

a. AFE distribution

b. Normal simulation threshold probability 0.25

c. OSU simulation

d. UKMO simulation

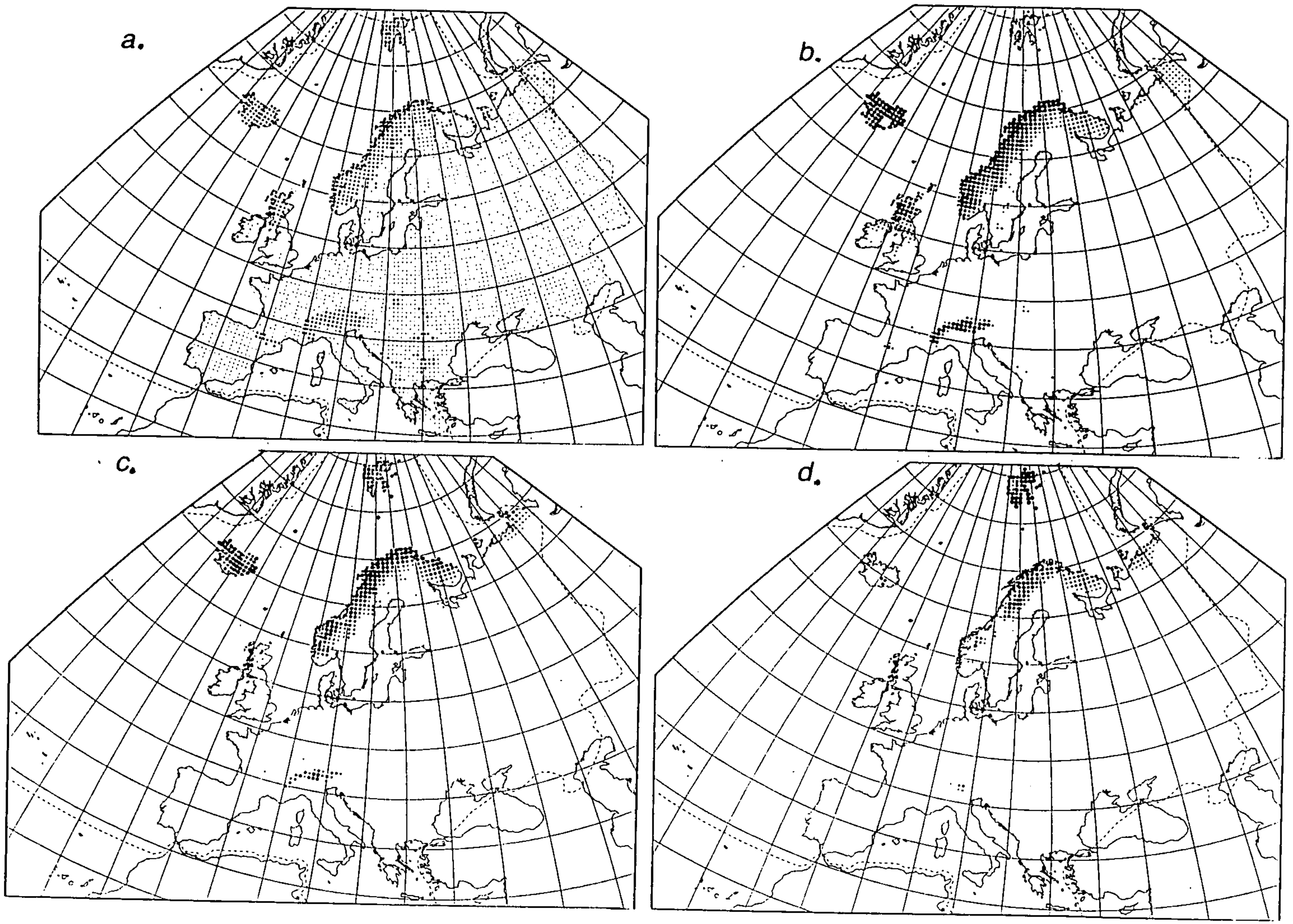

a.
b.
c.
d.

Figure 4.61

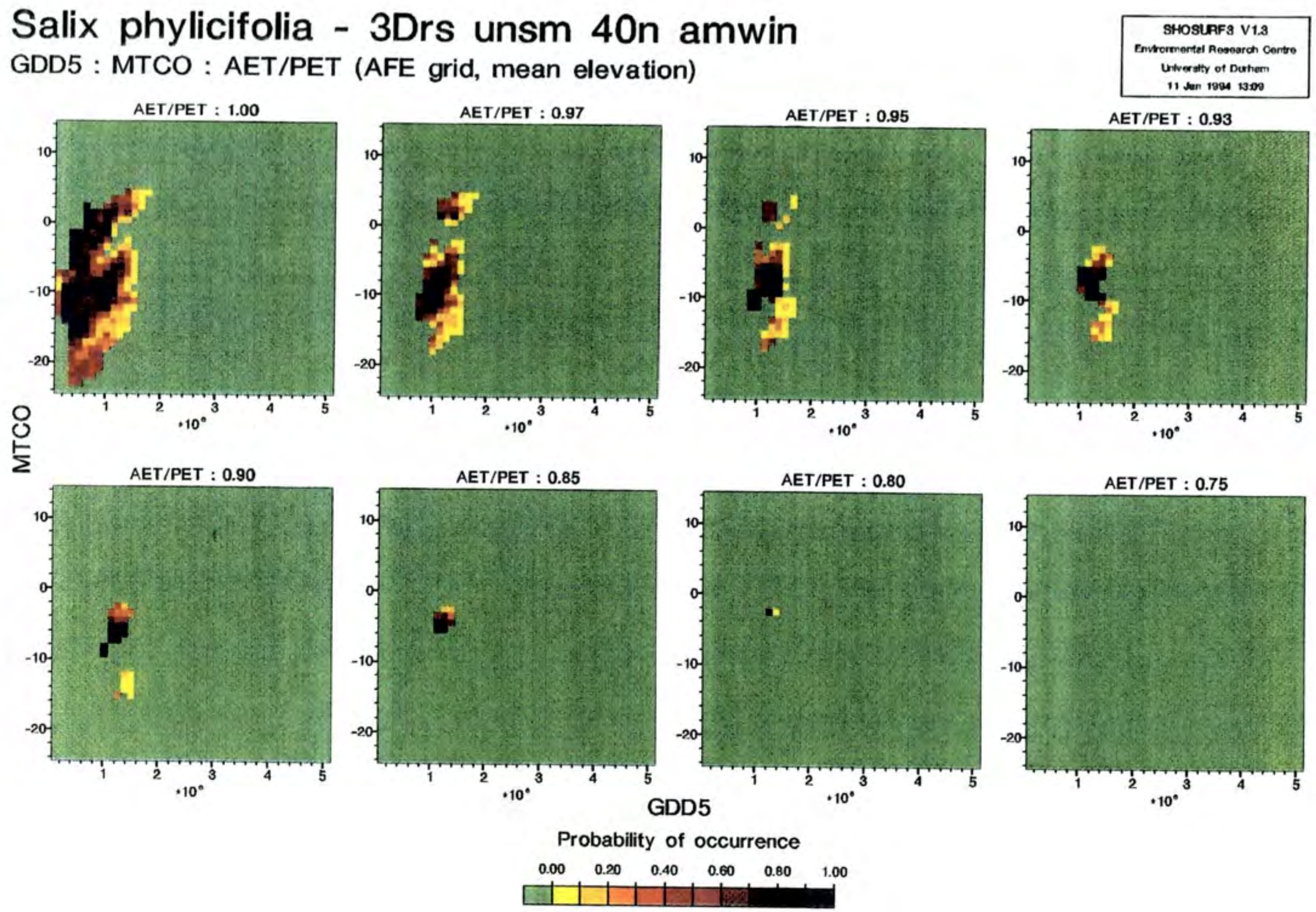

Salix phylicifolia - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
11 Jan 1994 13:09
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10³
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.62 ***Salix phylicifolia***

a. AFE distribution

b. Normal simulation threshold probability 0.35

c. OSU simulation

d. UKMO simulation

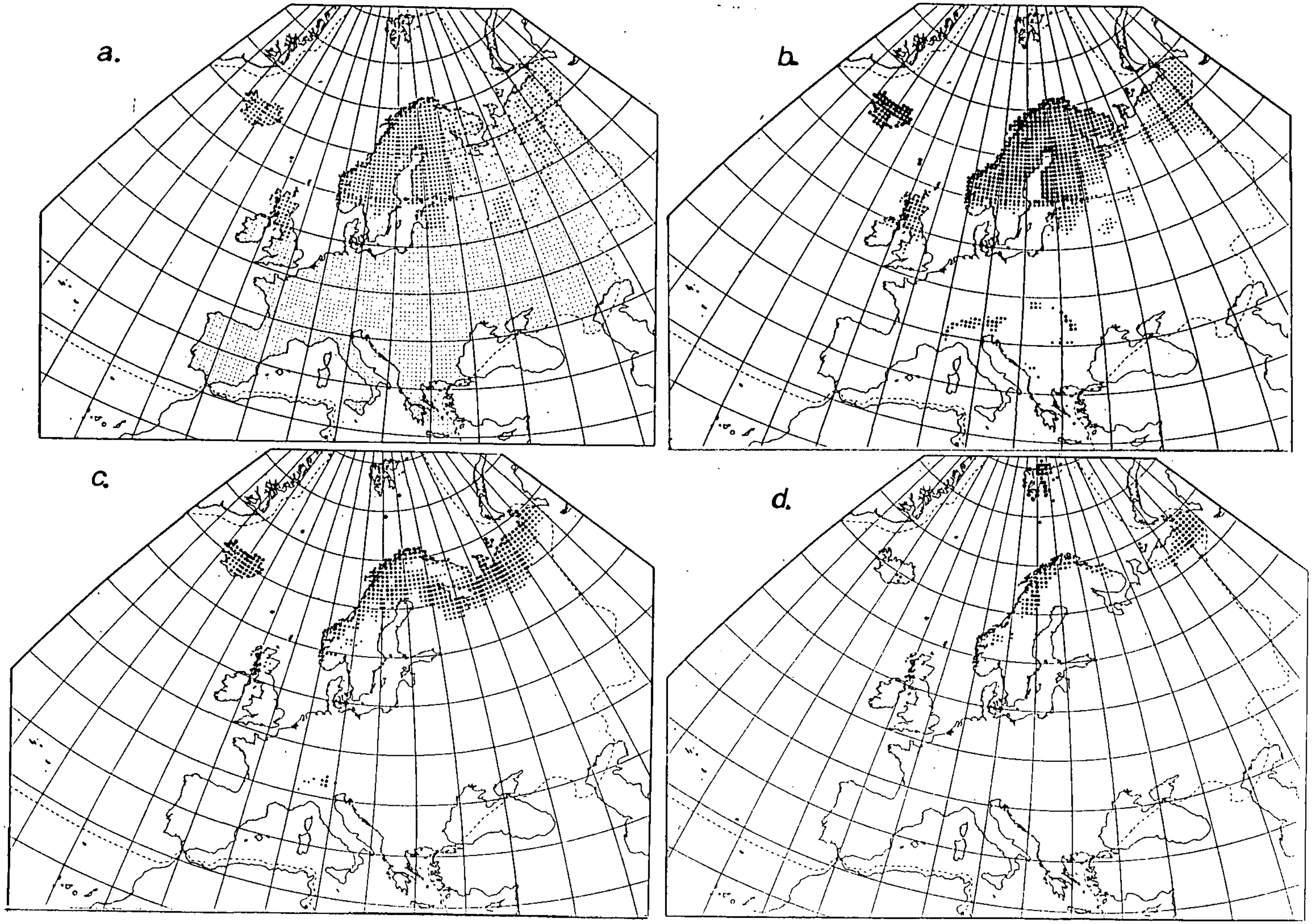

a.
b.
c.
d.

Figure 4.63

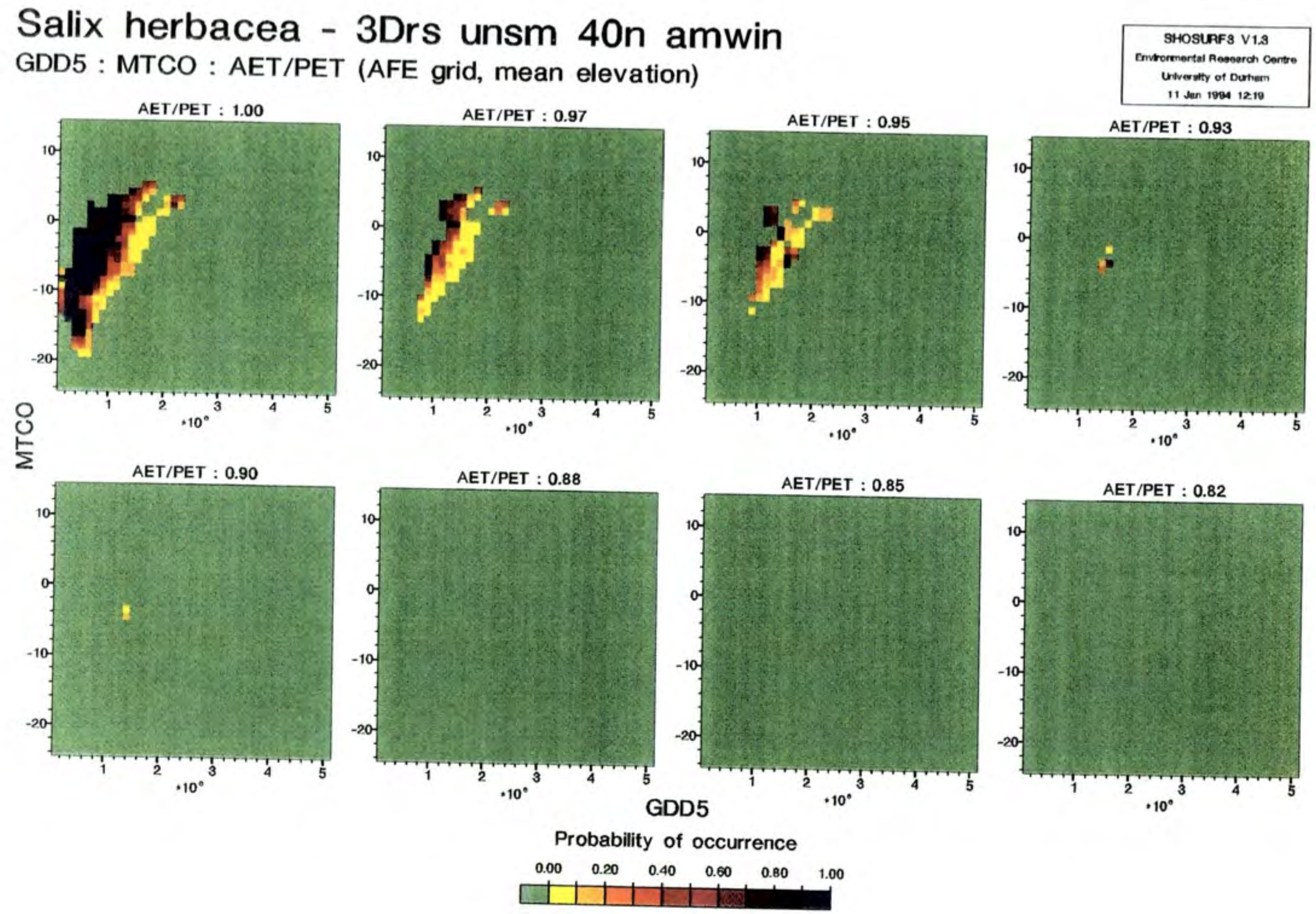

Salix herbacea - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
11 Jan 1994 12:19
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.88
AET/PET : 0.85
AET/PET : 0.82
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

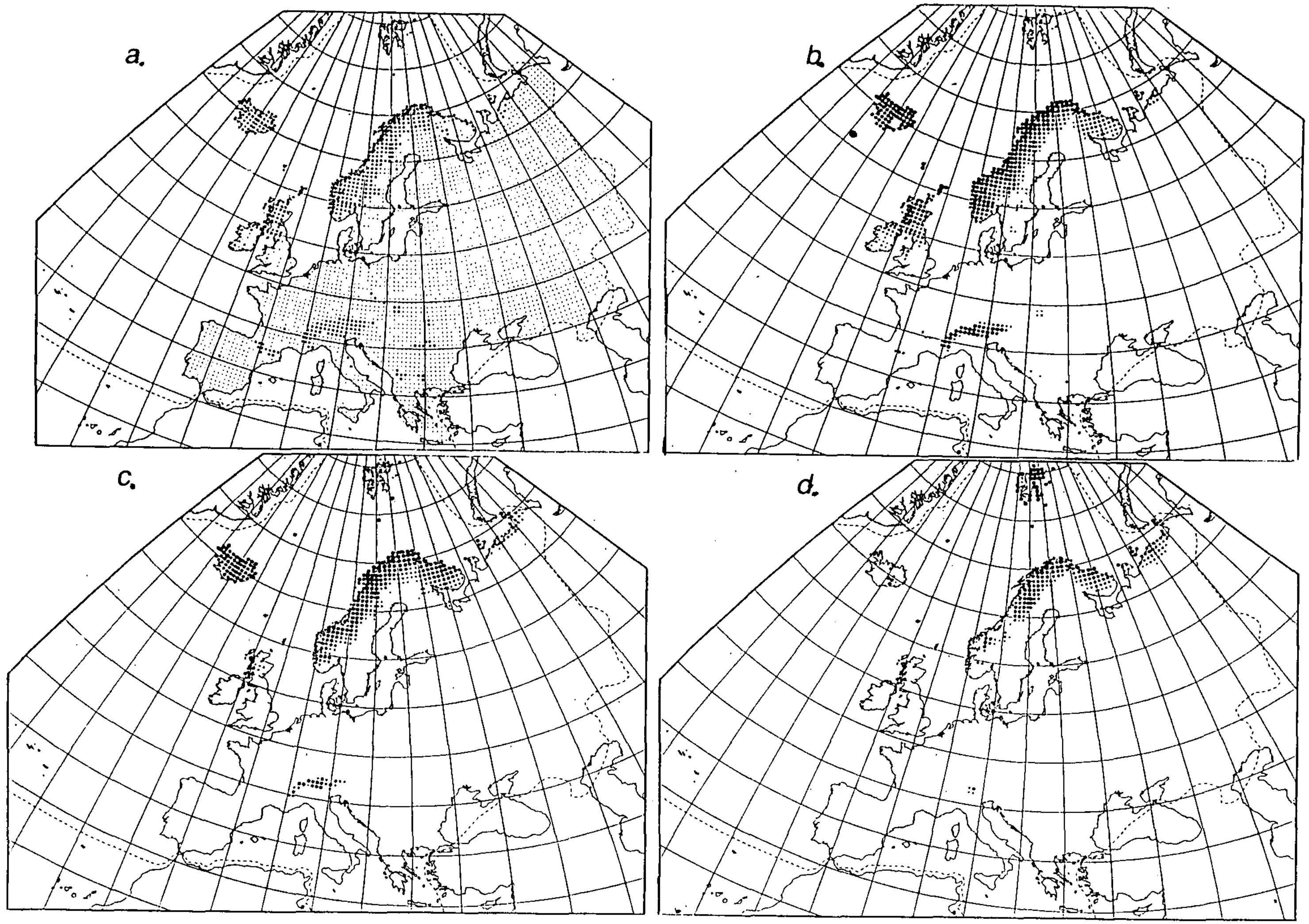
Figure 4.64 ***Salix herbacea***

a. AFE distribution

b. Normal simulation threshold probability 0.30

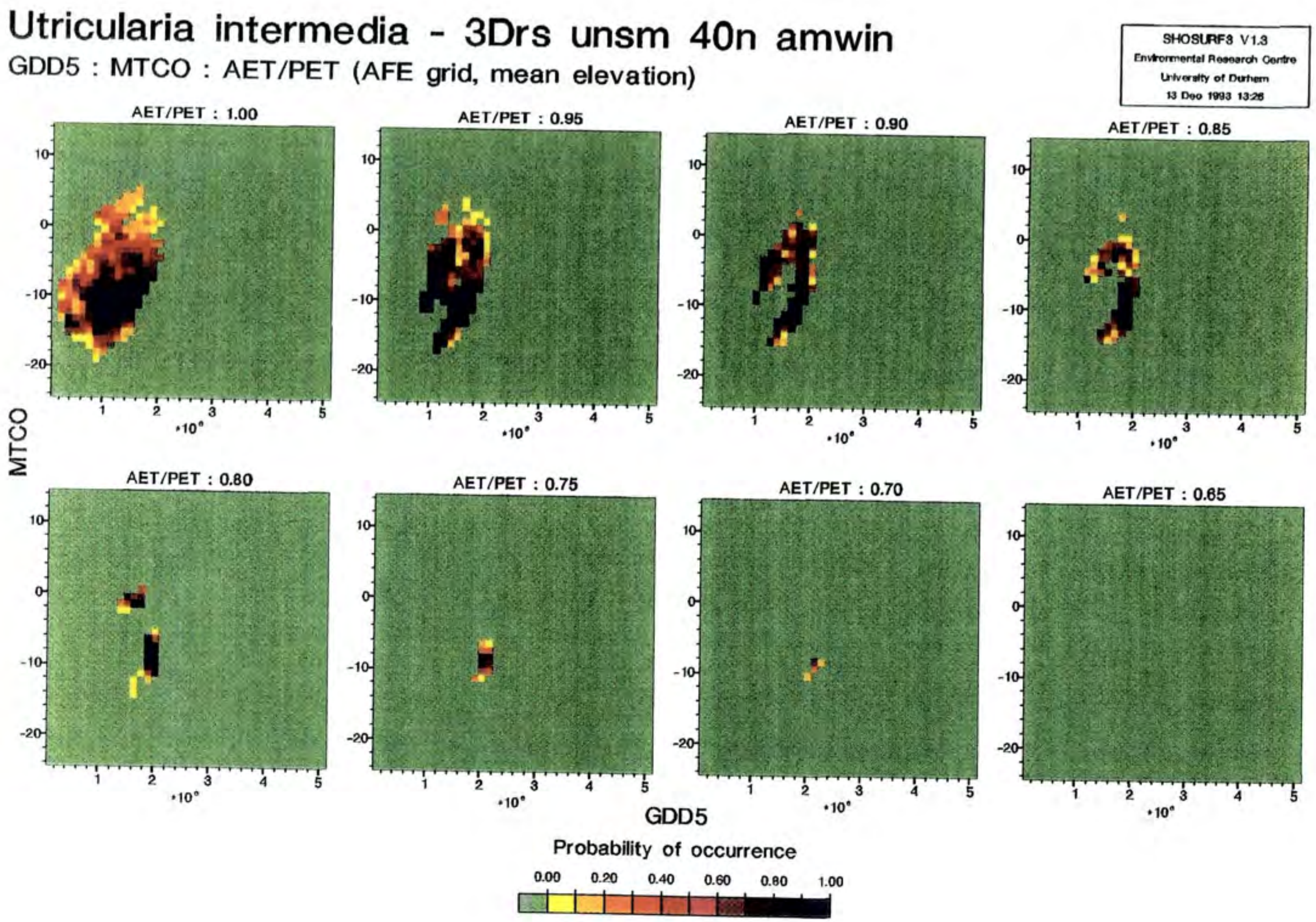
c. OSU simulation

d. UKMO simulation



a.
b.
c.
d.

Figure 4.65



Utricularia intermedia - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
13 Dec 1993 13:26
AET/PET : 1.00
AET/PET : 0.95
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
AET/PET : 0.70
AET/PET : 0.65
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.66 ***Utricularia intermedia***

a. AFE distribution

b. Normal simulation threshold probability 0.25

c. OSU simulation

d. UKMO simulation

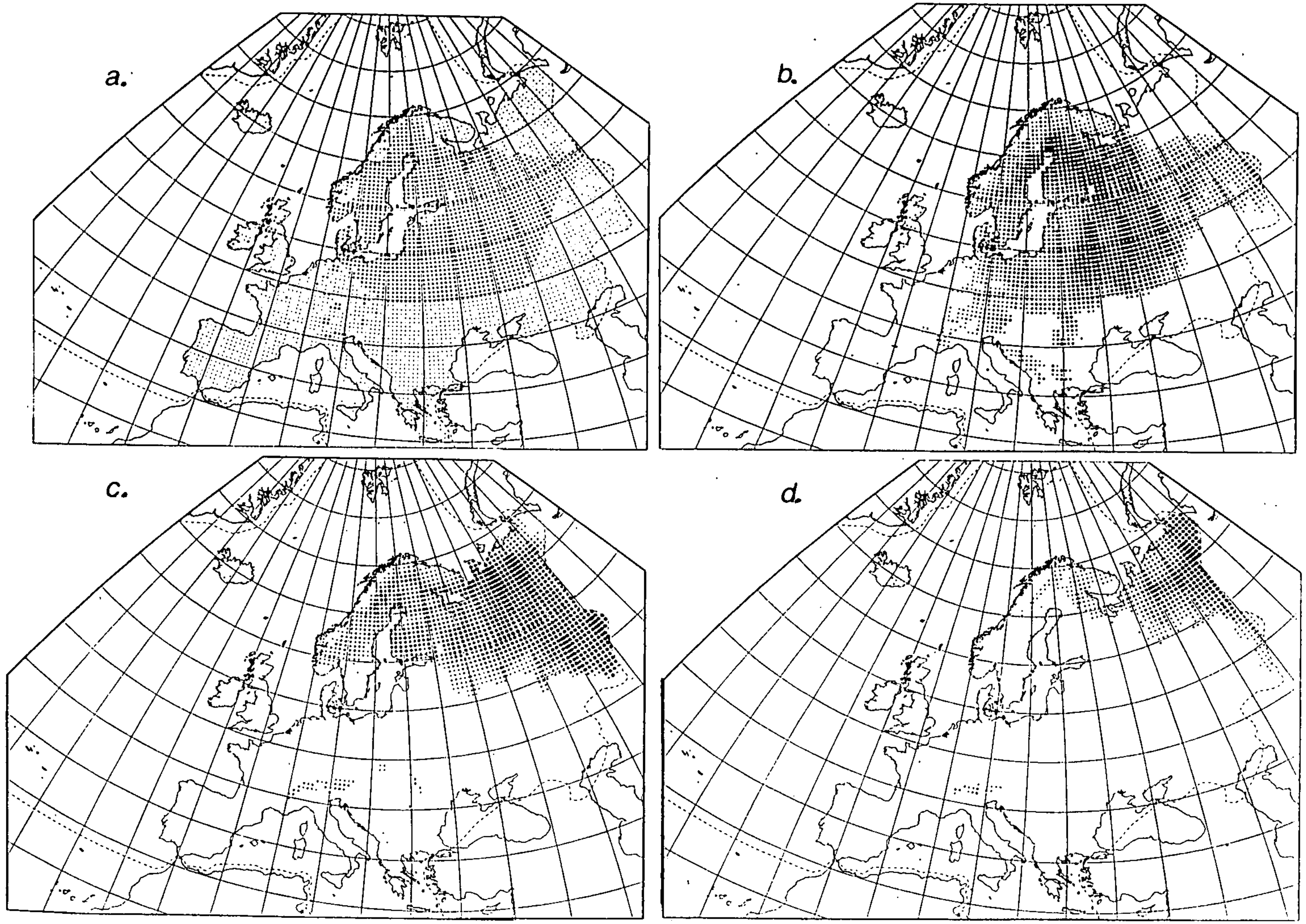
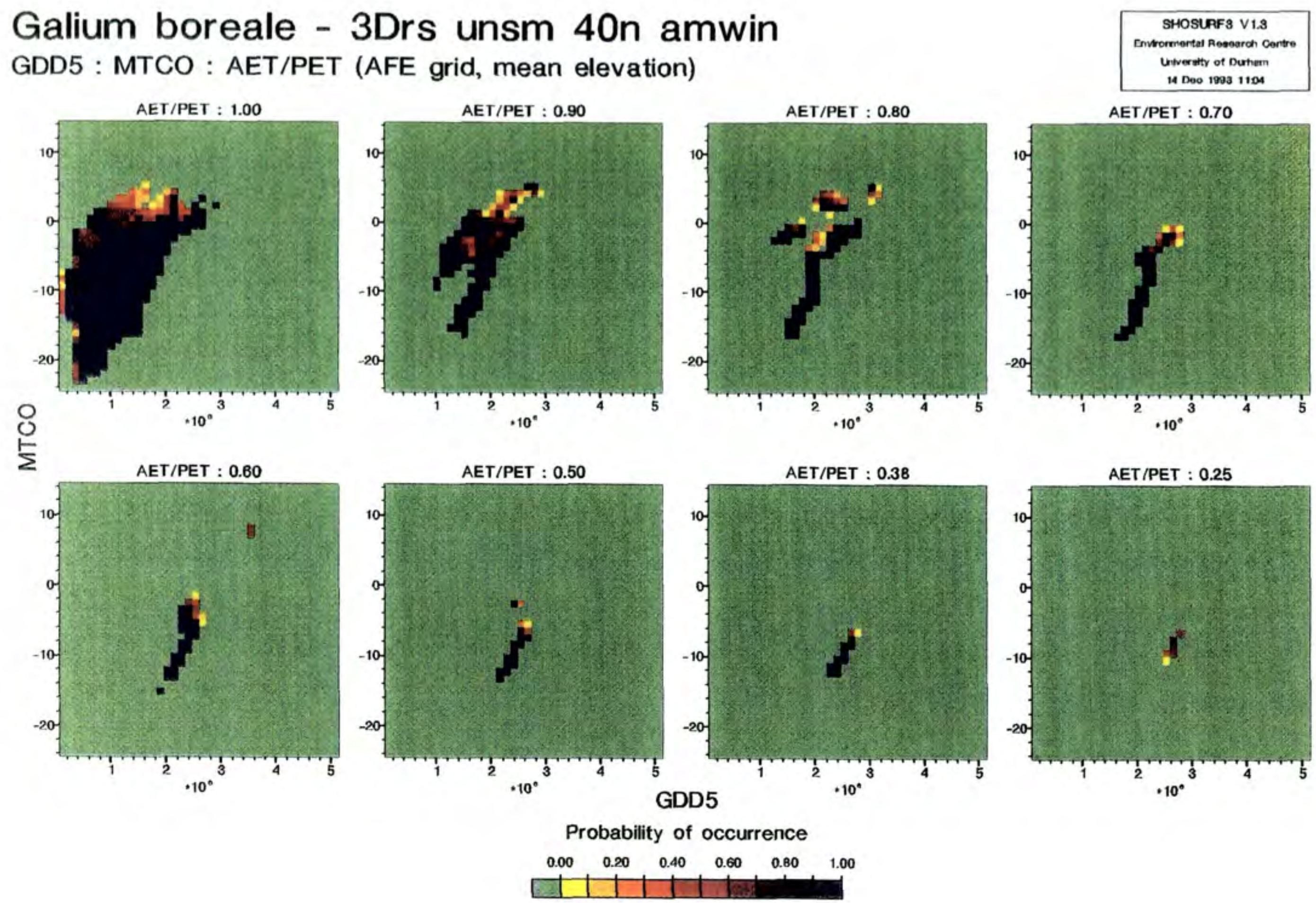

a.
b.
c.
d.

Figure 4.67



Galium boreale - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
14 Dec 1993 11:04
AET/PET : 1.00
AET/PET : 0.90
AET/PET : 0.80
AET/PET : 0.70
AET/PET : 0.60
AET/PET : 0.50
AET/PET : 0.38
AET/PET : 0.25
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.68 ***Galium boreale***

a. AFE distribution

b. Normal simulation threshold probability 0.50

c. OSU simulation

d. UKMO simulation

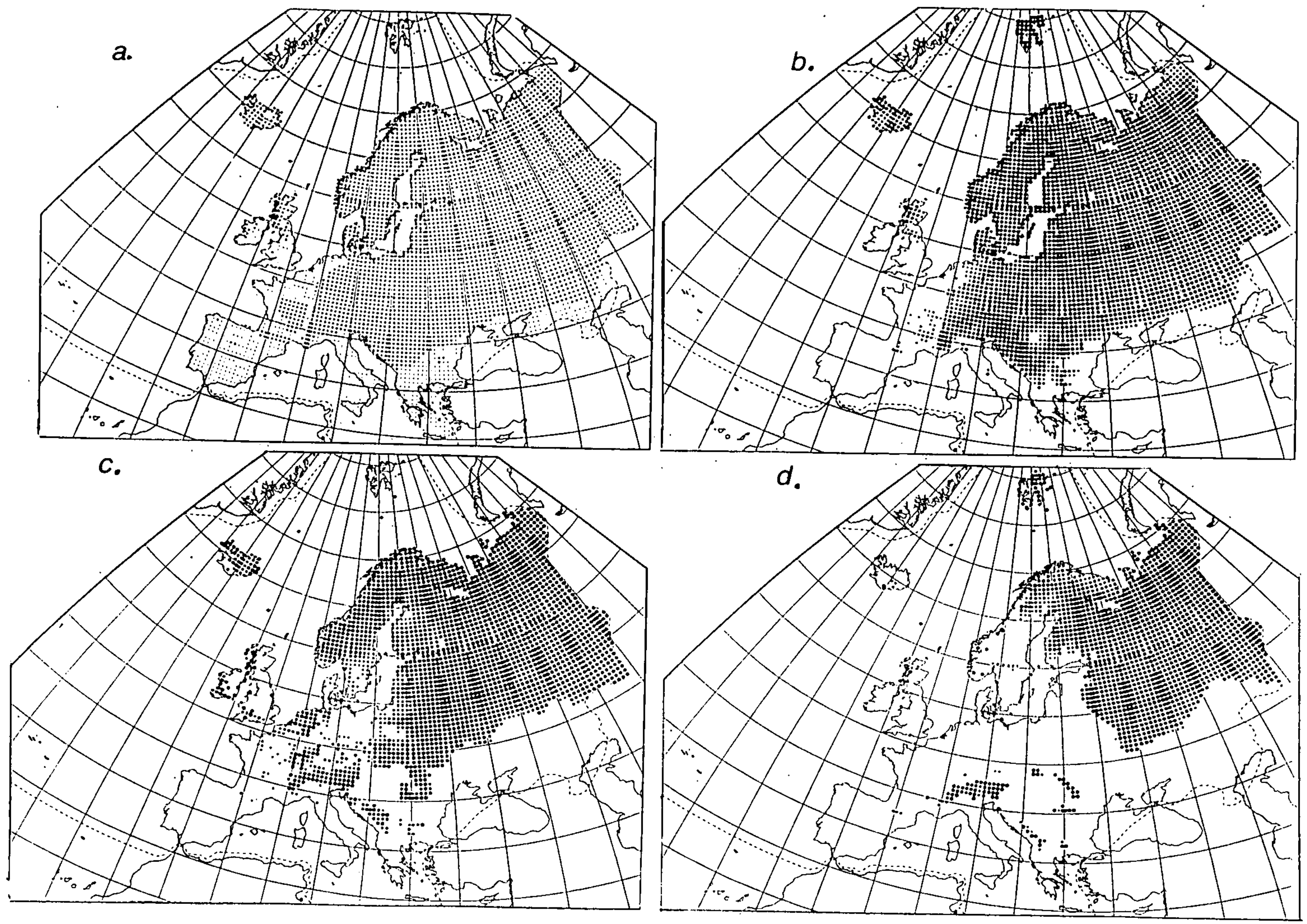
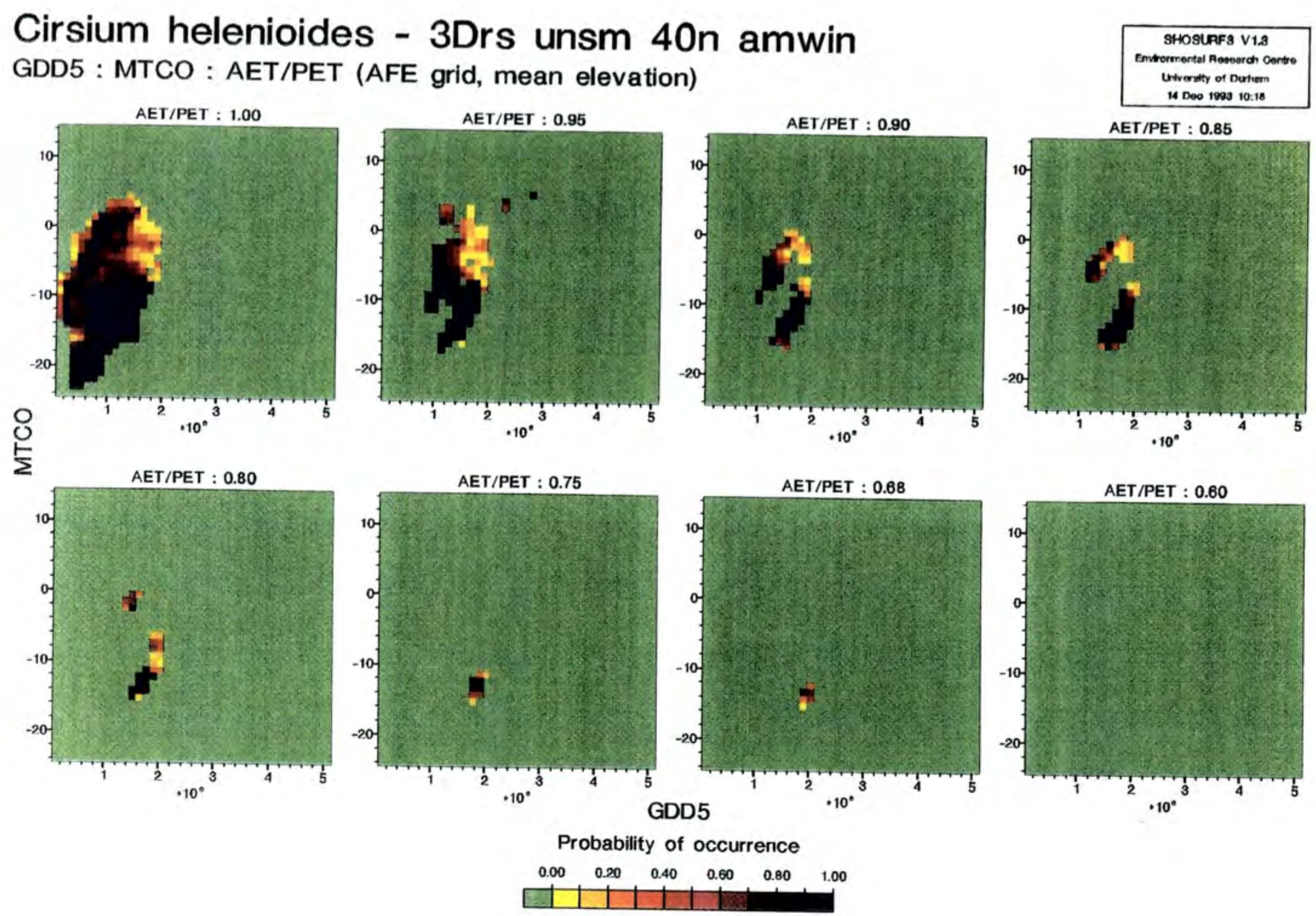

a.
b.
c.
d.

Figure 4.69



Cirsium helenioides - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
14 Dec 1993 10:18
AET/PET : 1.00
AET/PET : 0.95
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
AET/PET : 0.68
AET/PET : 0.60
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.70 ***Cirsium helenioides***

a. AFE distribution

b. Normal simulation threshold probability 0.50

c. OSU simulation

d. UKMO simulation

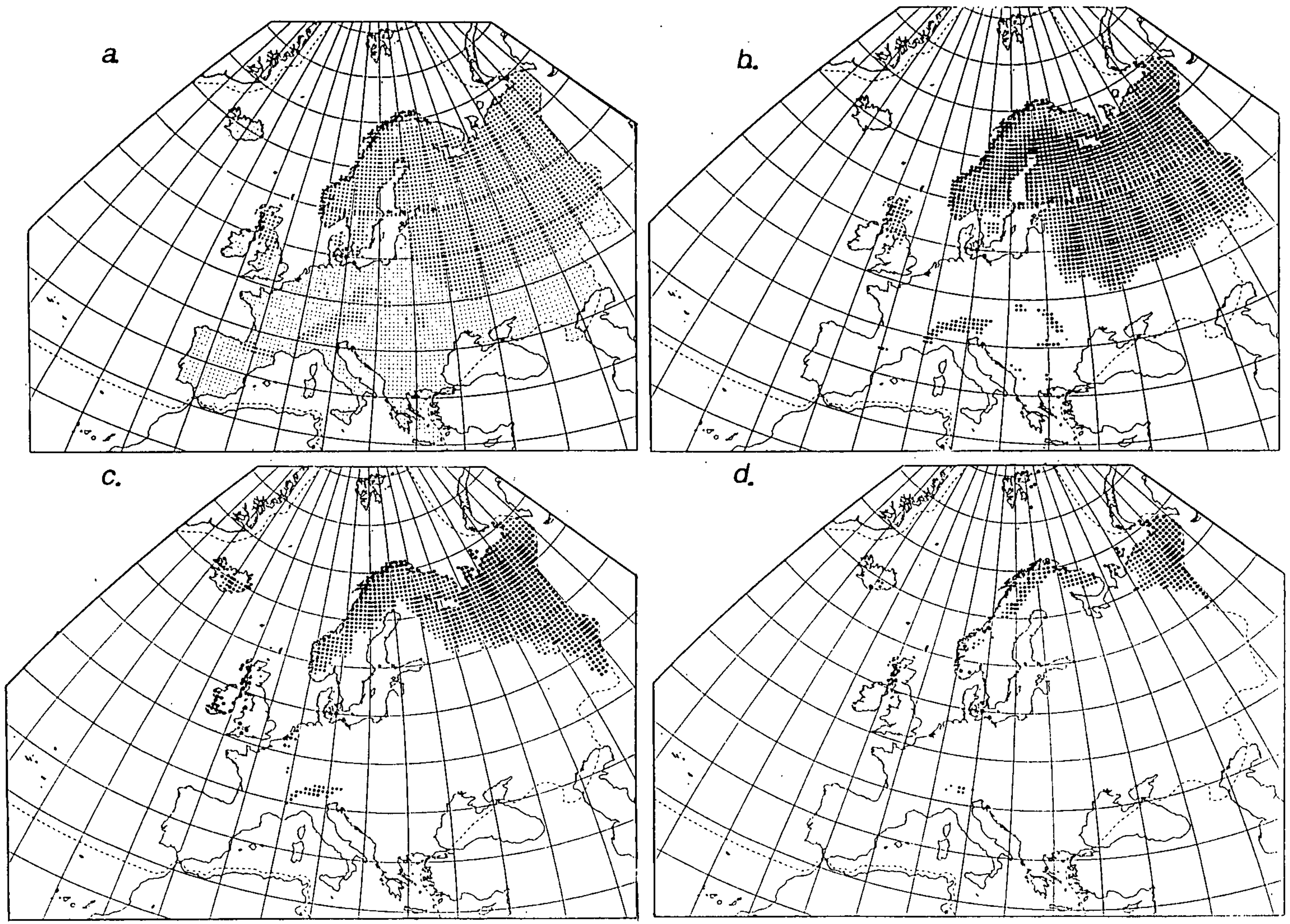

a
b.
c.
d.

Figure 4.71

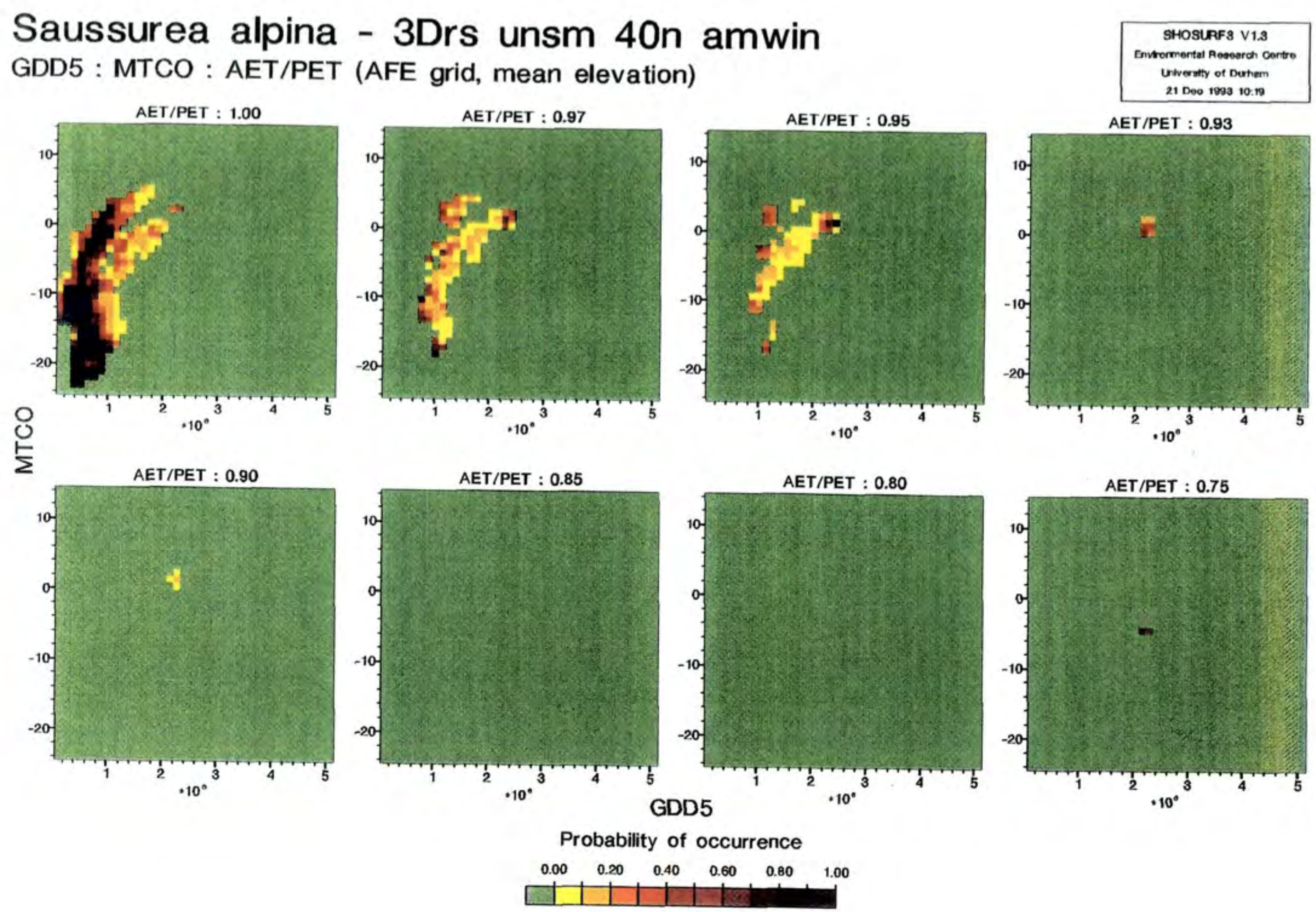

Saussurea alpina - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
21 Dec 1993 10:19
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10³
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.72 ***Saussurea alpina***

a. AFE distribution

b. Normal simulation threshold probability 0.35

c. OSU simulation

d. UKMO simulation

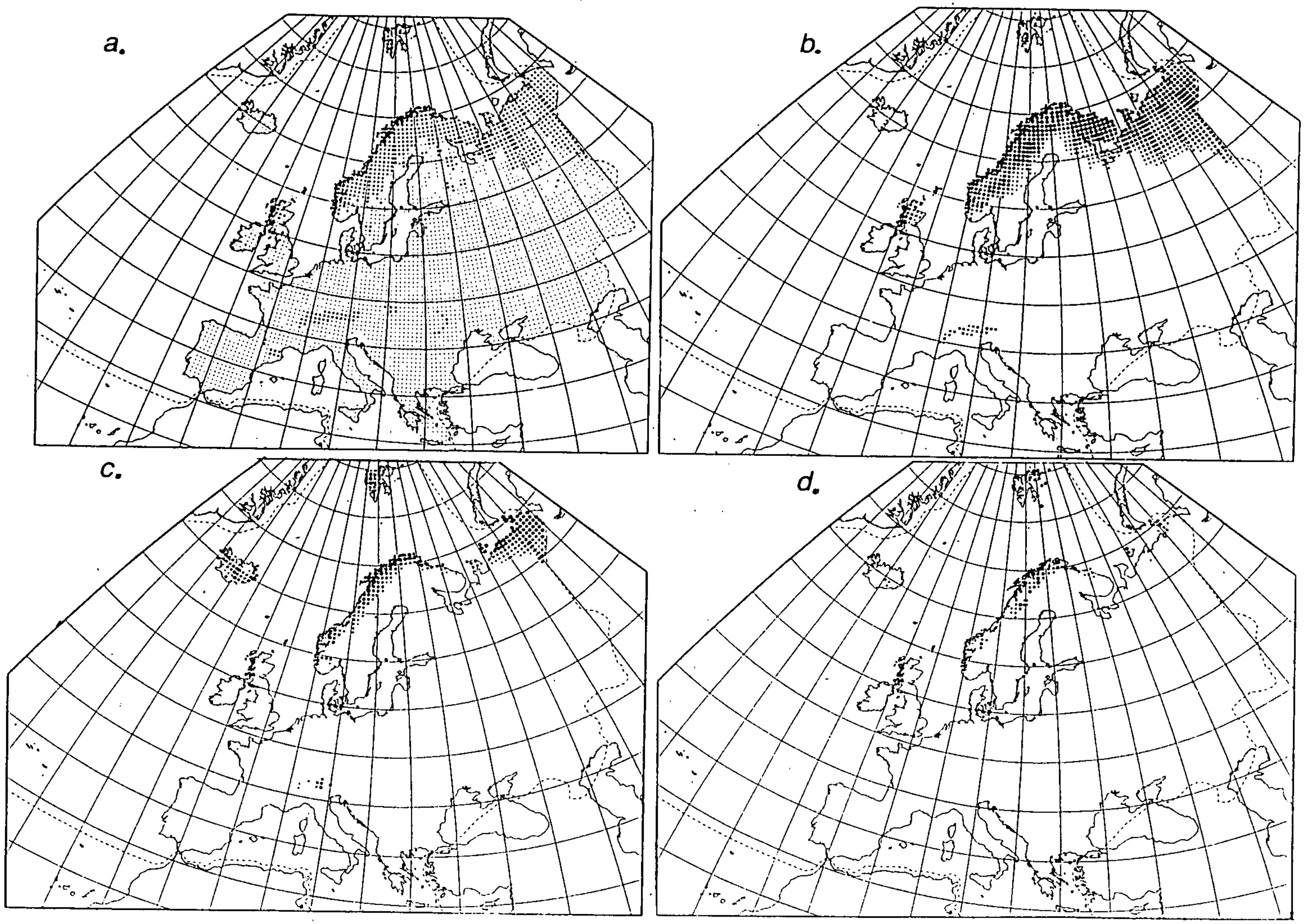

a.
b.
c.
d.

Figure 4.73

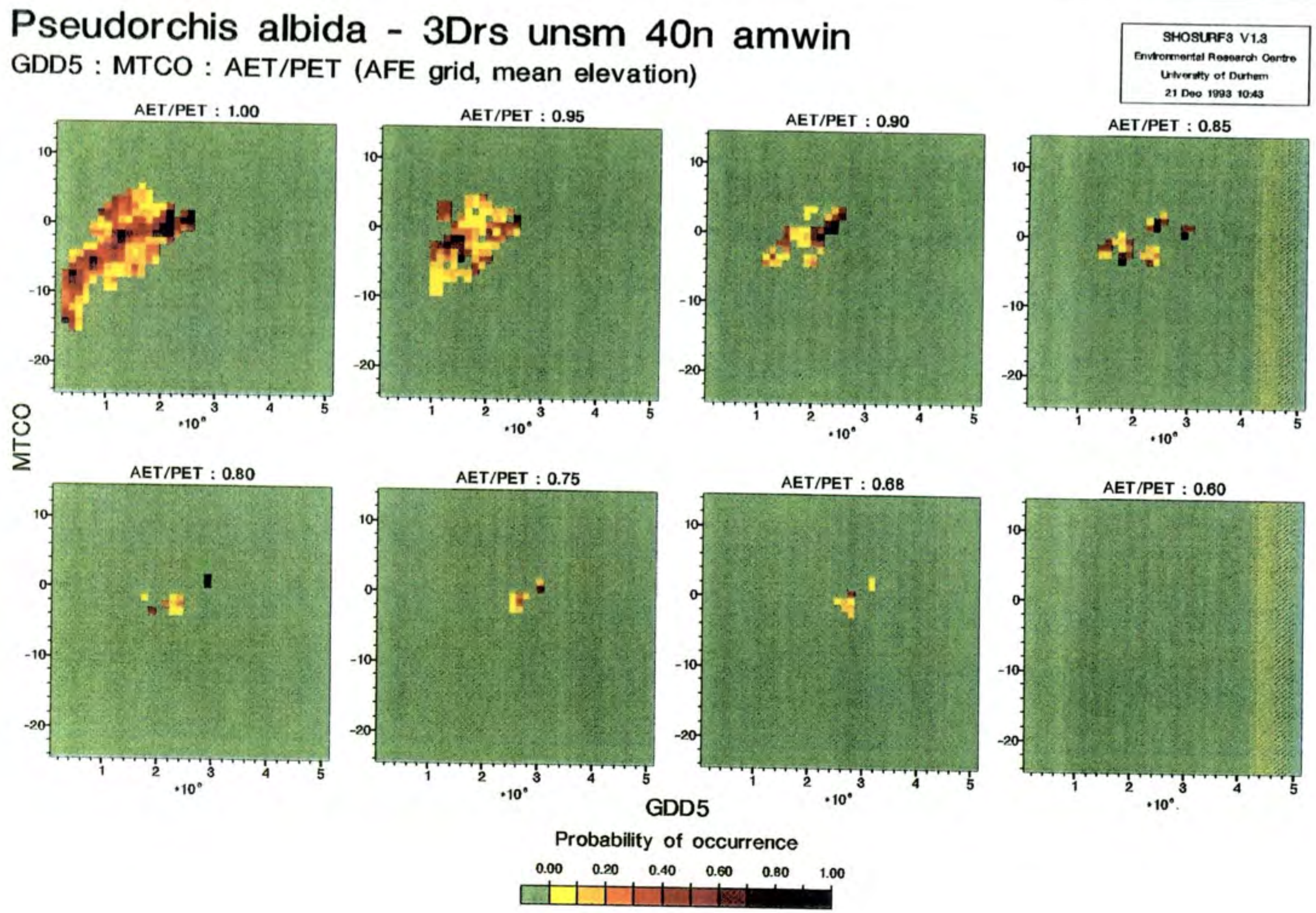

Pseudorchis albida - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
21 Dec 1993 10:43
AET/PET : 1.00
AET/PET : 0.95
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
AET/PET : 0.68
AET/PET : 0.60
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.74 ***Pseudorchis albida***

a. AFE distribution

b. Normal simulation threshold probability 0.30

c. OSU simulation

d. UKMO simulation

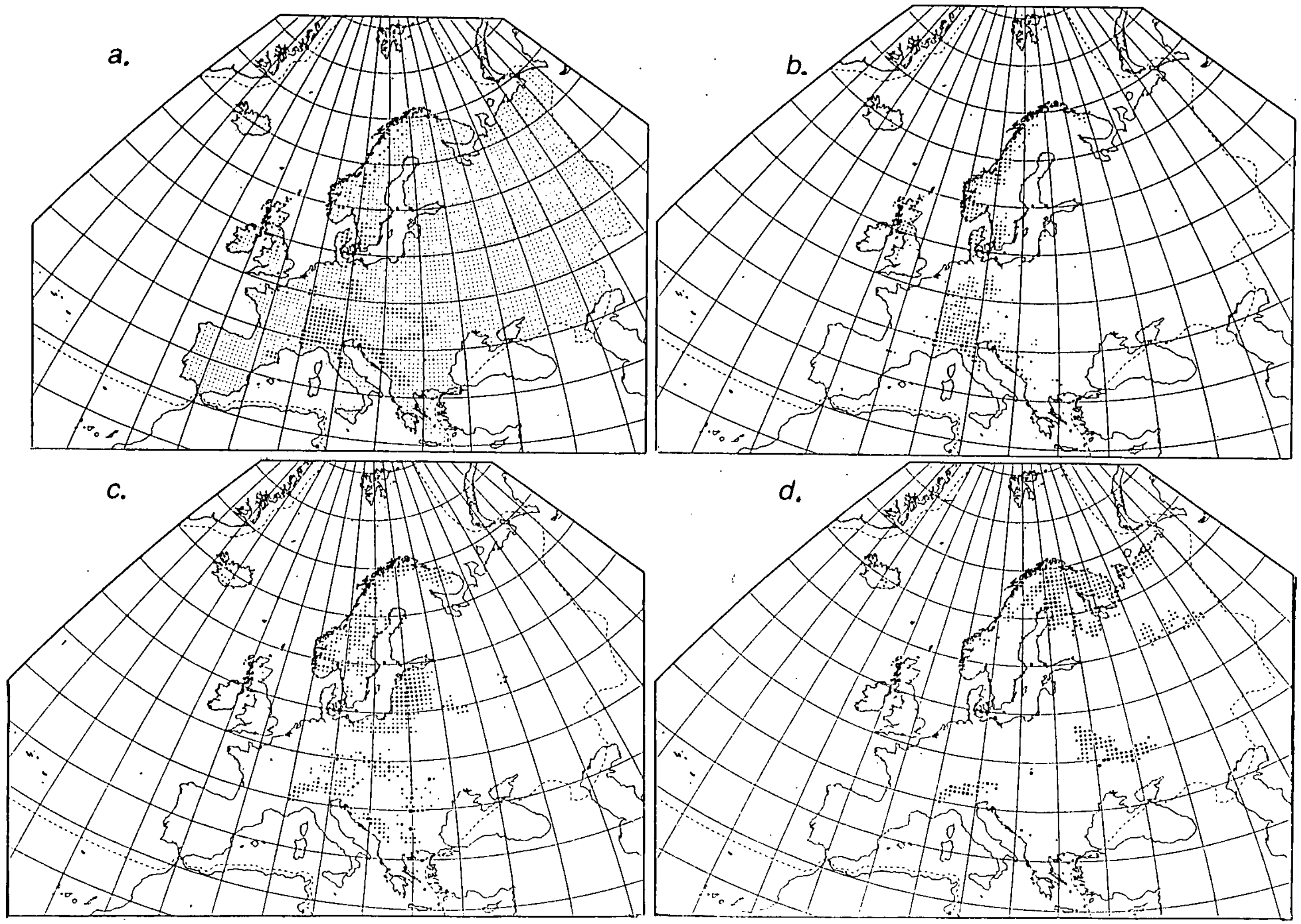
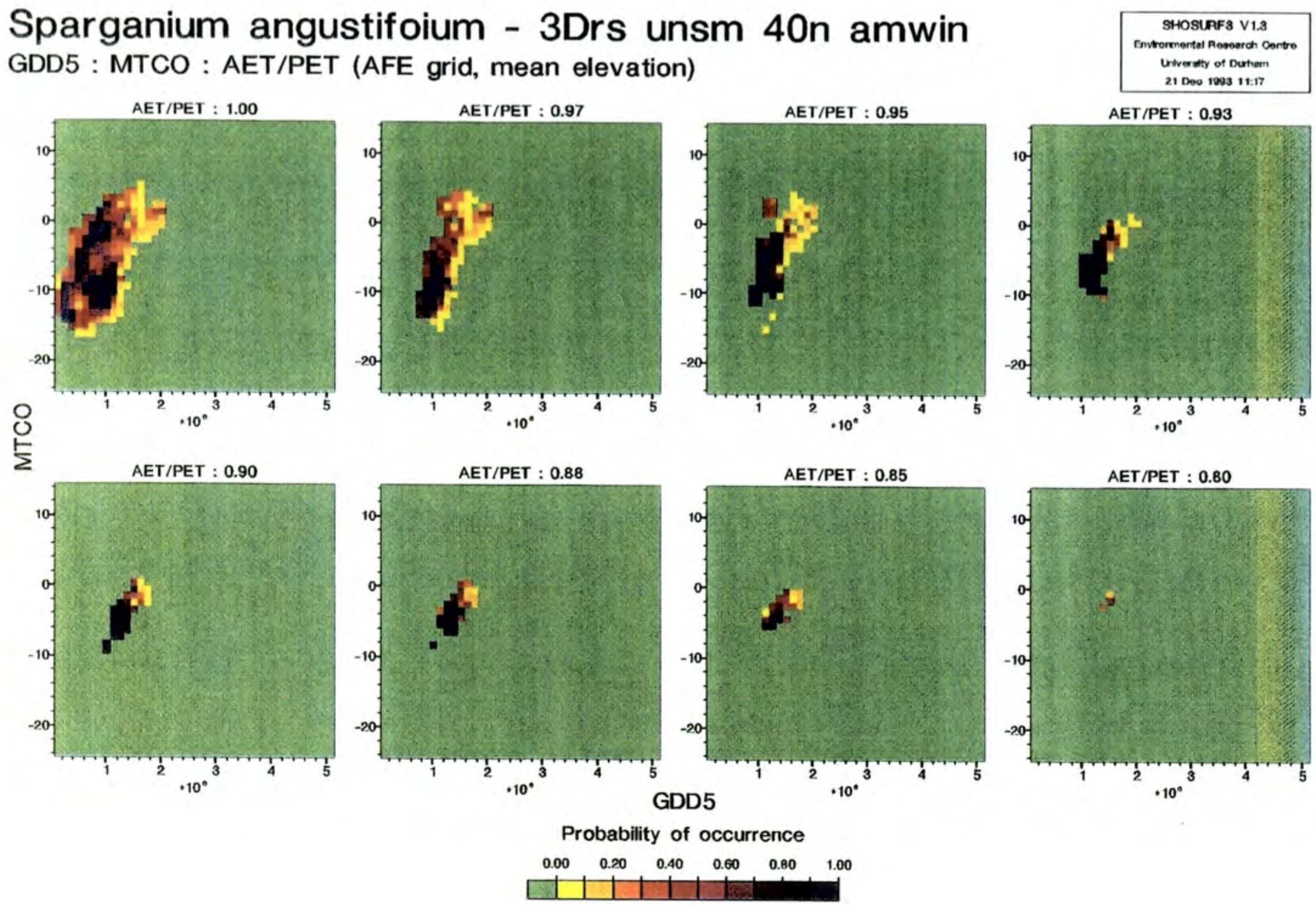

a.
b.
c.
d.

Figure 4.75



Sparganium angustifoium - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
21 Dec 1993 11:17
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.88
AET/PET : 0.85
AET/PET : 0.80
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.76 ***Sparganium angustifolium***

a. AFE distribution

b. Normal simulation threshold probability 0.35

c. OSU simulation

d. UKMO simulation

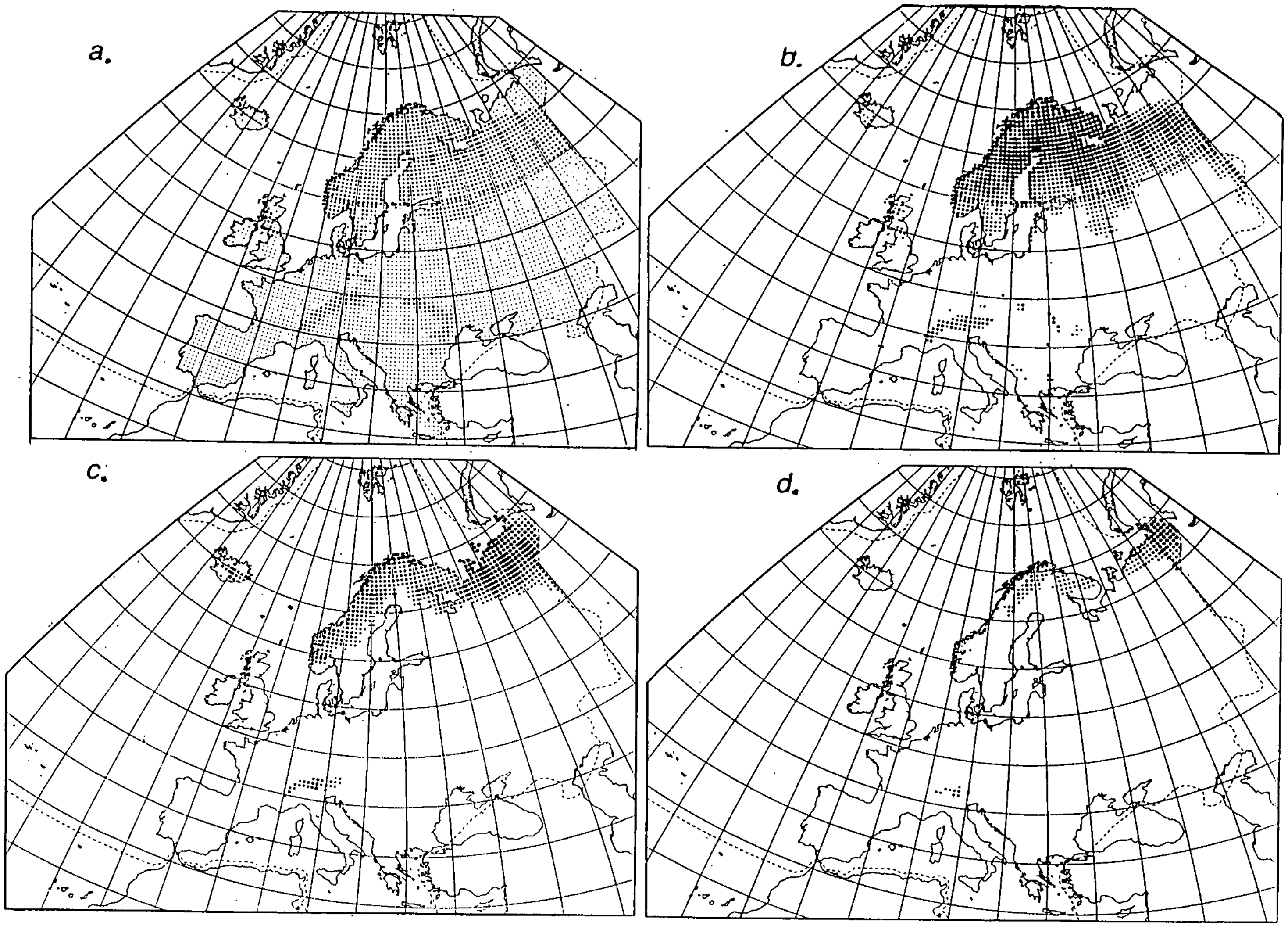
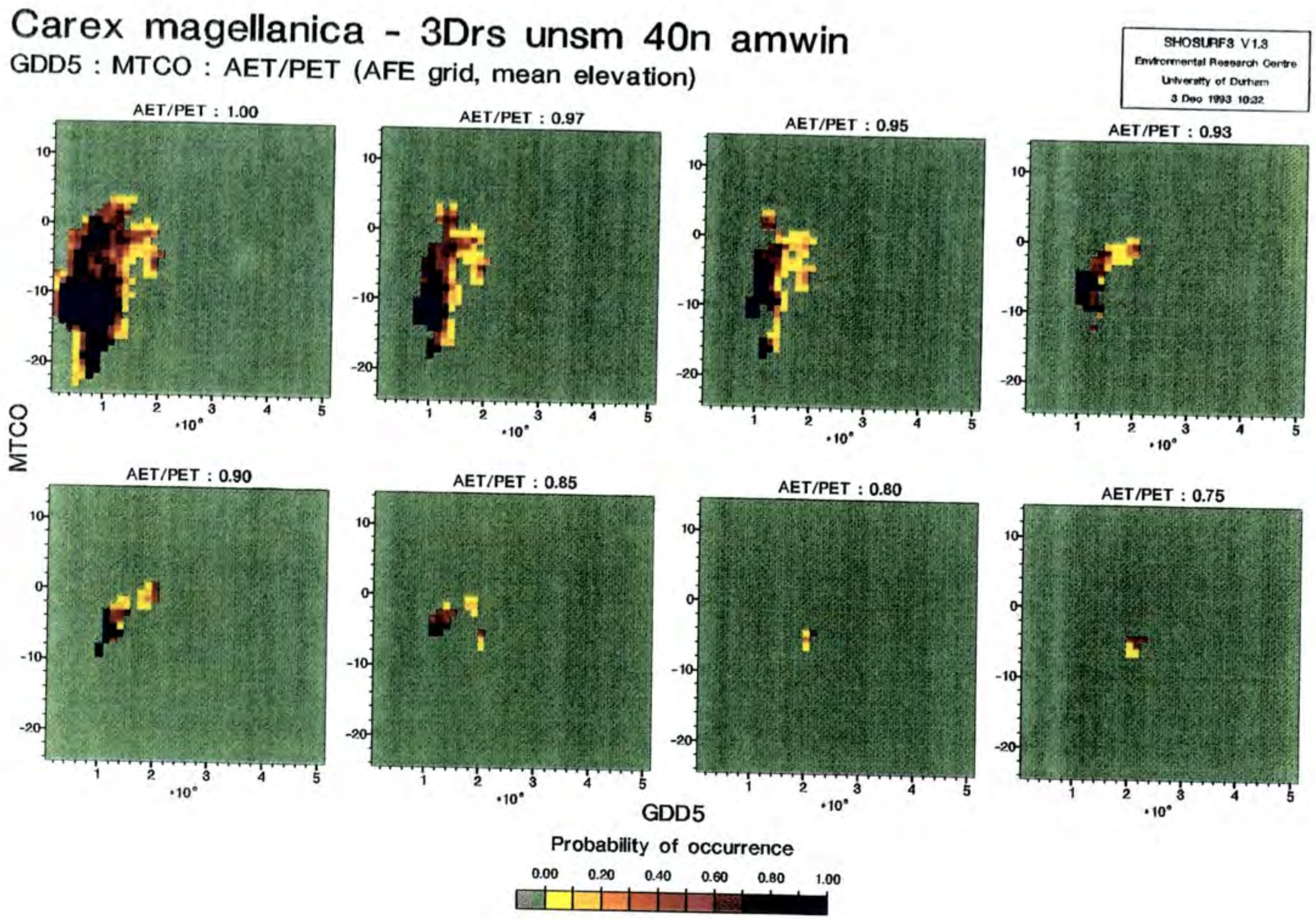

a.
b.
c.
d.

Figure 4.77



Carex magellanica - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 10:32
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00 0.20 0.40 0.60 0.80 1.00

Figure 4.78 ***Carex magellanica***

a. AFE distribution

b. Normal simulation threshold probability 0.40

c. OSU simulation

d. UKMO simulation

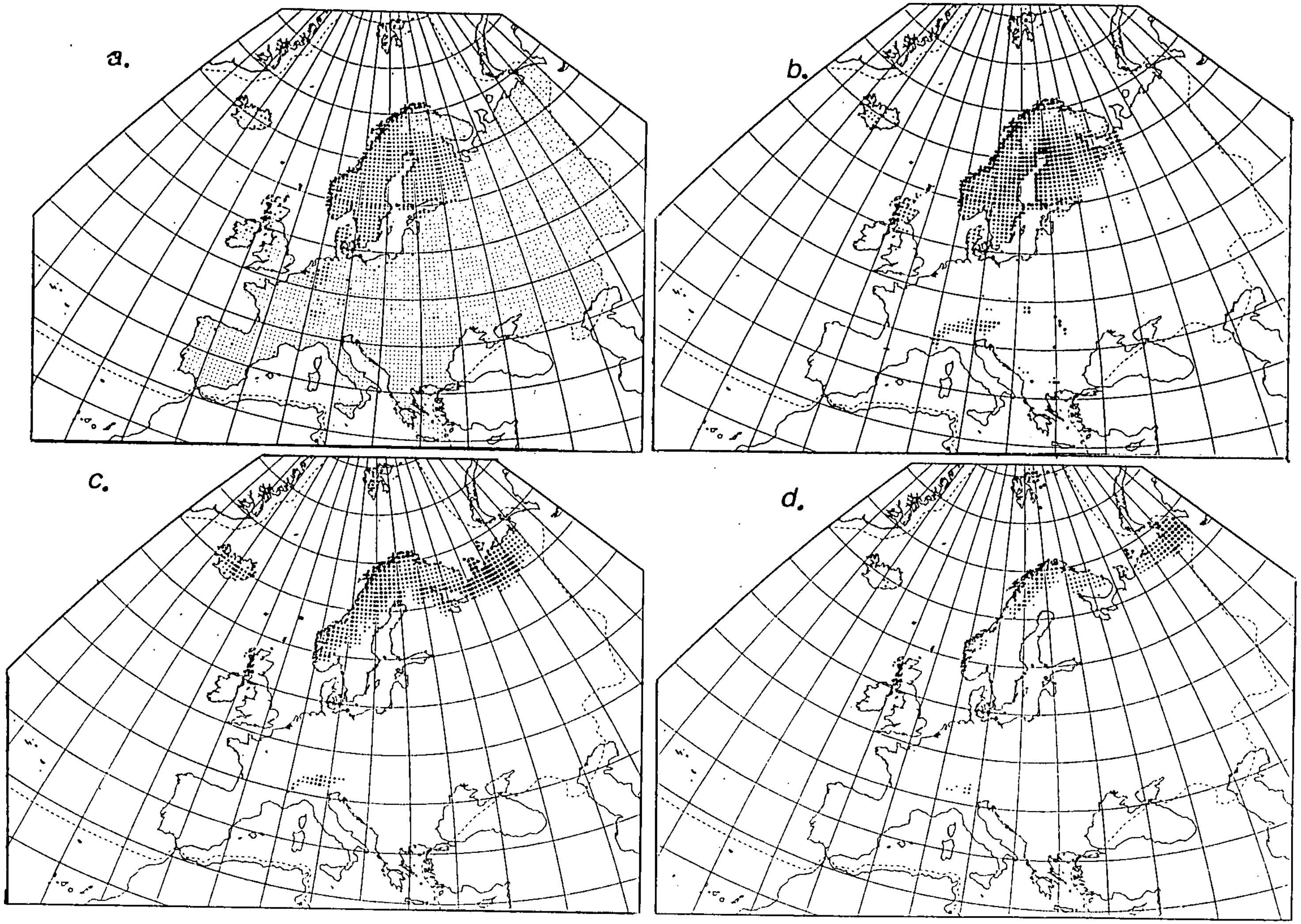

a.
b.
c.
d.

Figure 4.79

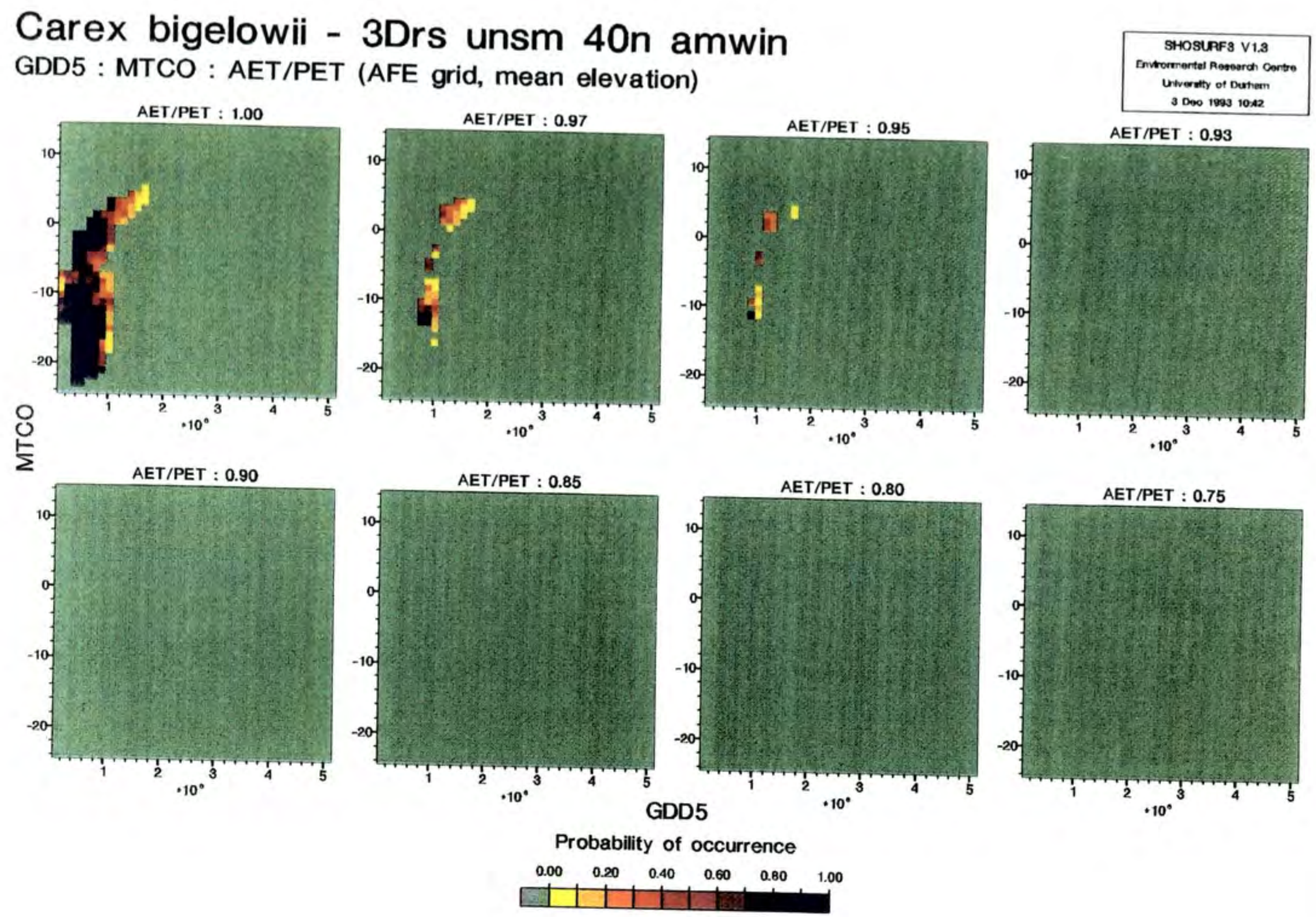

Carex bigelowii - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 10:42
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

Figure 4.80 ***Carex bigelowii***

a. AFE distribution

b. Normal simulation threshold probability 0.25

c. OSU simulation

d. UKMO simulation

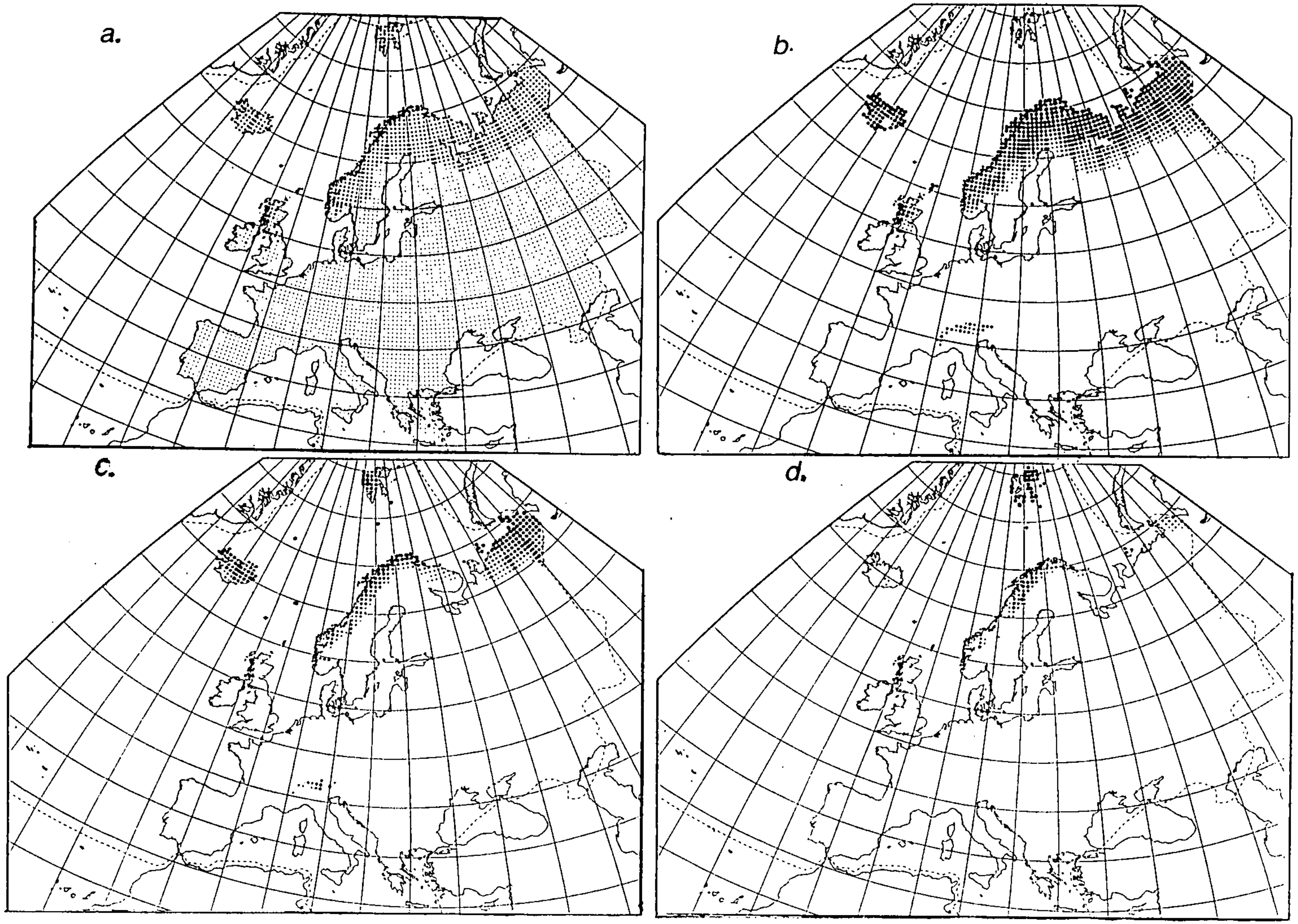

a.
b.
c.
d.

Figure 4.81

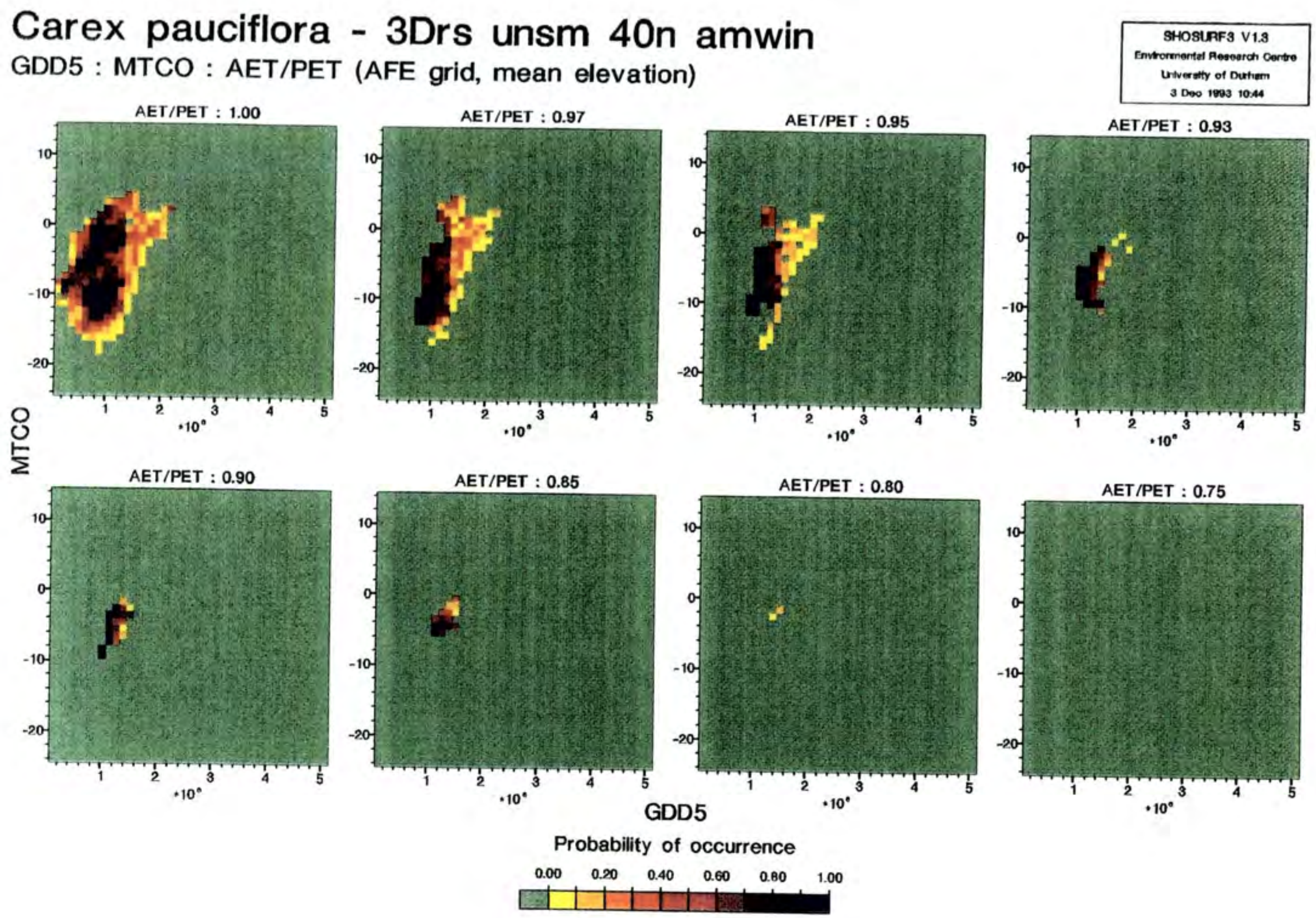

Carex pauciflora - 3Drs unsm 40n amwin
GDD5 : MTCO : AET/PET (AFE grid, mean elevation)
SHOSURF3 V1.3
Environmental Research Centre
University of Durham
3 Dec 1993 10:44
AET/PET : 1.00
AET/PET : 0.97
AET/PET : 0.95
AET/PET : 0.93
AET/PET : 0.90
AET/PET : 0.85
AET/PET : 0.80
AET/PET : 0.75
MTCO
GDD5
*10°
Probability of occurrence
0.00
0.20
0.40
0.60
0.80
1.00

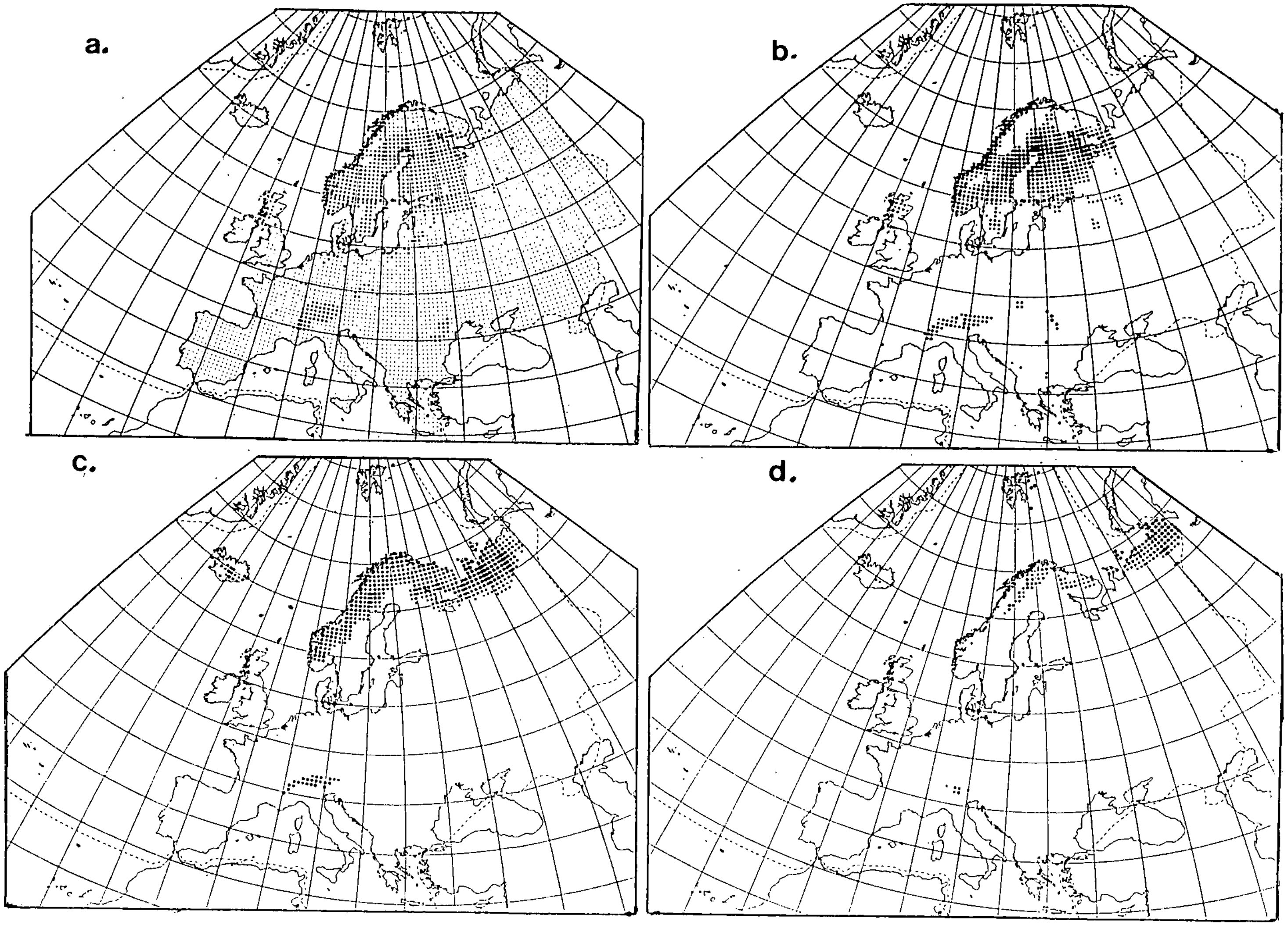
Figure 4.82 ***Carex pauciflora***

a. AFE distribution

b. Normal simulation threshold probability 0.50

c. OSU simulation

d. UKMO simulation


a.
b.
c.
d.

CHAPTER 5

Species monitoring

In order that the growth of selected plant species can be monitored over a period of years, sites have been identified. The sites are located in areas where there is unlikely to be disturbance and for ease of relocation. The method used for recording varies depending upon the site and the species. In some cases the number of plants or shoots are counted, the percentage cover of a given area by the plant may be estimated, or photography is used. The recording of some plants is based on the "Recording Method for the long term monitoring of calcicolous grasslands in Britain" (Rich *et al.*, unpublished). (see Appendix I) The sites are located, where possible, in relation to obvious geographical features such as boulders, walls, fences etc., so that they can be readily relocated. Photographs sketches and measurements are used to aid the relocation of the sites.

5.1 Sites

5.1.1 *Hymenophyllum wilsonii*

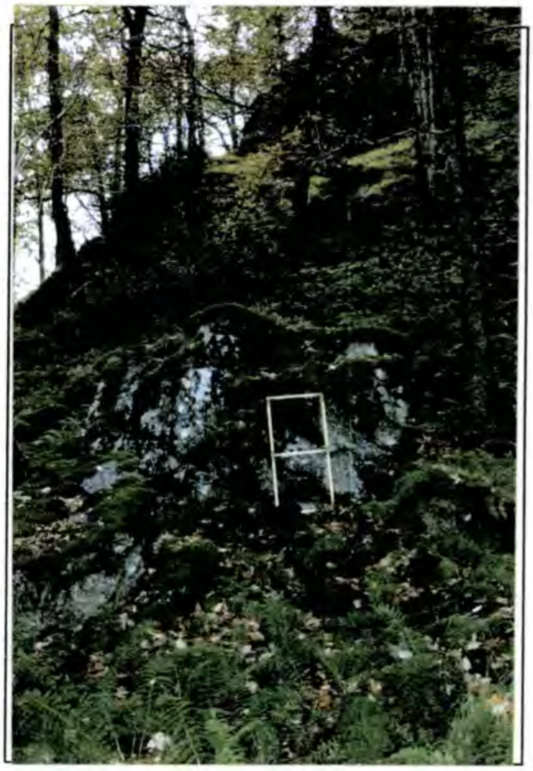


Plate 5.1.1a.1

Johnny's Wood

5.1.1a Johnny's Wood is an SSSI under the management of the National Trust. It is situated on the hard acidic type of rock of the Borrowdale Volcanic Series. On a rocky slope it is an oak-wood with birch, hazel, holly and rowan. There is little under scrub which is generally considered to be due to past management. *Hymenophyllum wilsonii* is found on a rock growing with bryophytes. The National Grid Reference is 35(NY)/254142, the altitude is 130 m, the rock has a north-easterly aspect. The site is reached by entering the wood by a stile on the footpath between Longthwaite Youth Hostel and Longthwaite which skirts the wood. After crossing the stile turn left, cross-over the remains of a wall and walk towards three holly trees. Climb and the rock is facing. (see plate 5.1.1a.1) The fern growth is recorded by photographs.

Plate 5.1.1b.1

Glencoyne Wood

5.1.1b Glencoyne Wood is a mixed deciduous wood by Ullswater under the management of the National Trust. It is of a similar type to Johnny's Wood. Two separate sites, where *Hymenophyllum wilsonii* is growing, have been located. After crossing the cattle grid. the first site is on a rocky outcrop on the left (see plate 5.1.1b.1). The National Grid Reference is 35(NY)/386183 the altitude 170 m and facing north. The fern is growing with bryophytes. The second site, **5.1.1c**, is high on the rocky cliff side of Moss Crag. National Grid Reference is 35(NY)/384183 at an altitude of 300 m the aspect is northerly. The site is above an elm tree (see plate 5.1.1c.1). The sites are reached by the sign post for Glencoyne Wood and following the path over the cattle grid, the first site is on the left. The second site is reached by following the path until you reach a gate into field on the right, and on the left there are many large boulders (see plates 5.1.1c.2 & 5.1.1c.3). Turn left at this point and climb up to cliff face, looking for elm tree. The fern is recorded by photographs.

Plate 5.1.1c.1

Glencoyne Wood

Elm tree

Plate 5.1.1c.2

Glencoyne Wood

Gate

Plate 5.1.1c.3

Glencoyne Wood

Large Boulders

Plate 5.1.1d.1

Guerness Gill

Approaching the site

Plate 5.1.1d.2

Guerness Gill

Site

5.1.1d Guerness Gill is a stream entering Hawes Water on the eastern side. The site is upstream on its southern side (right side when facing upstream from the road). Follow the stream crossing a small stream and after passing a large boulder. *Hymenophyllum wilsonii* is growing below a short waterfall on rocks by the stream. There is a fence on the opposite side of the stream and a birch tree above the rocks (see plates 5.1.1d.1 & 5.1.1d.2). The National Grid Reference is 35(NY)/483133 the altitude 340 m and the rocks are north facing. The fern is recorded by photographs.

5.1.2 *Draba incana*

5.1.2a Thistle Green on Cronkley Fell in the Upper Teesdale NNR, is an SSSI managed by English Nature. On the summit of Cronkley Fell there are extensive exposures of sugar limestone. Thistle Green is an enclosure in which there has been extensive wind erosion. *Draba incana* is growing on a blown out sugar limestone pavement. The National Grid Reference is 35(NY)/843285, the altitude 540 m and the site has an open aspect. The recording is by the method for long term monitoring of calcicolus grassland. The plot was not marked with wire loops due to the shallow nature of the soil, it can be relocated from the patterns of boulders which were carefully photographed.(see plates 5.1.2a.1, 5.1.2a.2, 5.1.2a.3 & Fig. 5.1.2a.1) The number of plants growing in the area is estimated.

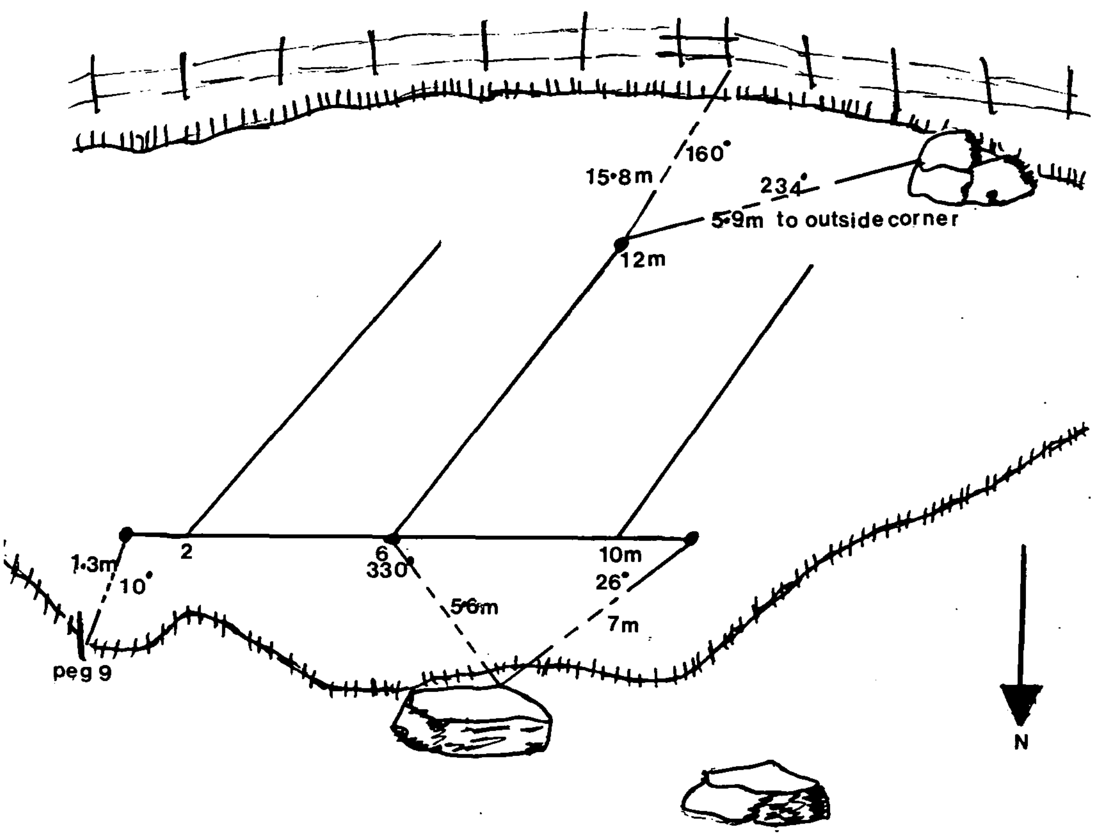


Figure 5.1.2a.1

Plate 5.1.2a.1

Thistle Green

Plate 5.1.2a.2

Thistle Green

Central Tape

Plate 5.1.2a.3

Thistle Green

Base Line Tape

5.1.2b Tailbrigg Gill is an enclosed area in which sheep graze. *Draba incana* is growing in very isolated locations on the limestone cliffs on the west side of Rigg Beck. It is an open turf area with outcrops of limestone rocks. The National Grid Reference is 35(NY)/810055, altitude is 430 m and the aspect is northeasterly. As the plants were so few the records were made by photography. The site of one plant growing on the cliff side was recorded by measurement from fence posts and a rock. (see plates 5.1.2b.1, 5.1.2b.2, 5.1.2b.3, & Fig. 5.1.2b.1). This site is on private land, which is farmed by Mr D.J. Dixon of Nateby, permission is required to visit the site.

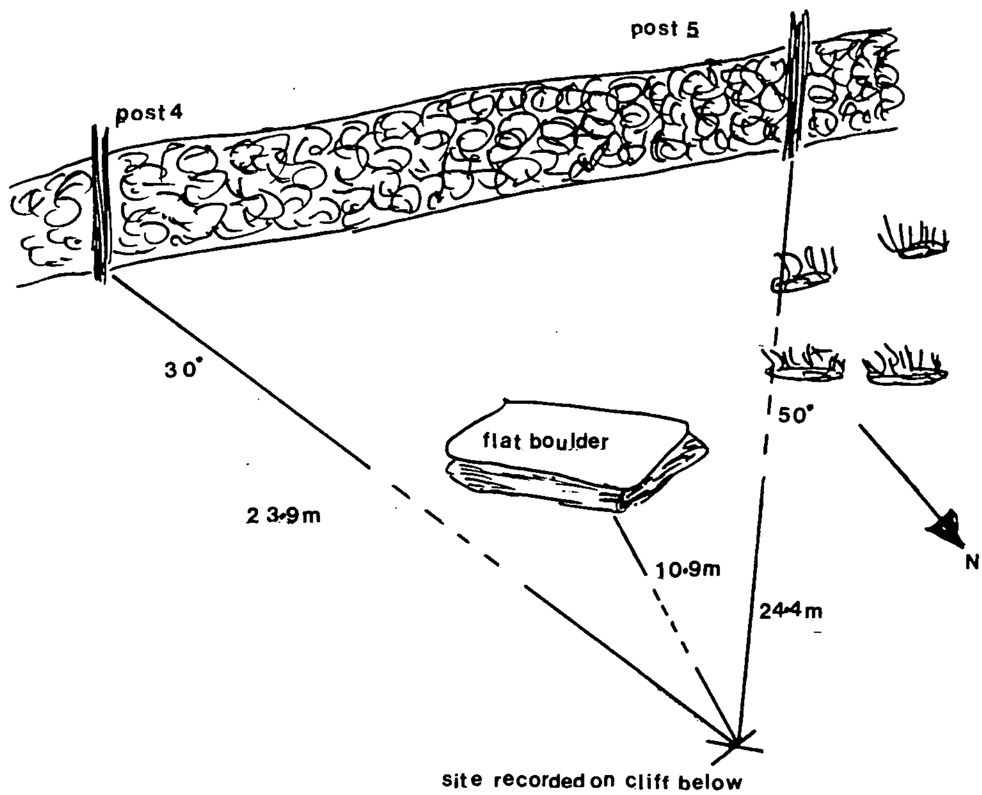


Figure 5.1.2b.1

Plate 5.1.2b.1

Tailbrigg Gill

Flat boulder

Plate 5.1.2b.2

Tailbrigg Gill

Fence Posts 4 & 5

Plate 5.1.2b.3

Tailbrigg Gill

Point above specimen

5.1.3 *Rubus chamaemorus*

5.1.3 Moorhouse is a NNR in the northern Pennines, managed by English Nature. Two sites of blanket peat bog were selected. The sites are both grazed by sheep, and the *Rubus chamaemorus* is growing with *Calluna vulgaris*, and species of cotton grass and sphagnum moss. The number of shoots of *Rubus chamaemorus* in the area is recorded.

5.1.3a above "Moorhouse" is relatively flat and has an open aspect, the National Grid Reference is 35(NY)/759327 and the altitude 590 m. This site was laid out by the method used for long term monitoring of calcicolous grassland. Wire loops were placed in the ground and also measurements taken from the stile, fence posts and a brick building. (see plates 5.1.3a.1, 5.1.3a.2, 5.1.3a.3 & Fig. 5.1.3a.1).

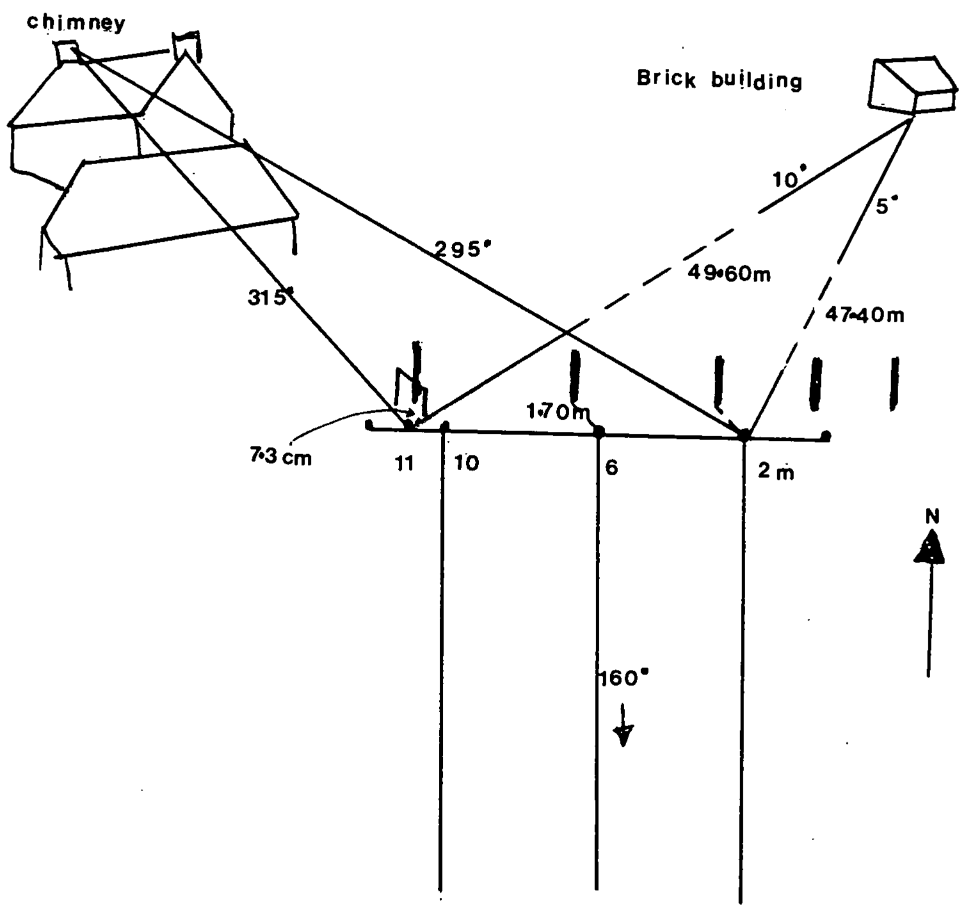


Figure 5.1.3a.1

Plate 5.1.3a.1

"Moor House"

Far Chimney

Plate 5.1.3a.2

Moor House

Brick Building

Plate 5.1.3a.3

Moor House

Stile

5.1.3b Trout Beck is above the Trout Beck weir and on a slight slope. The National Grid Reference is 35(NY)/757334 the altitude 550 m and the site is facing northnorthwest. The site was laid out as previous, it could be difficult to relocate as the only landmark is a dug out area. (see plates 5.1.3b.1, 5.1.3b.2, & Fig. 5.1.3b.1).

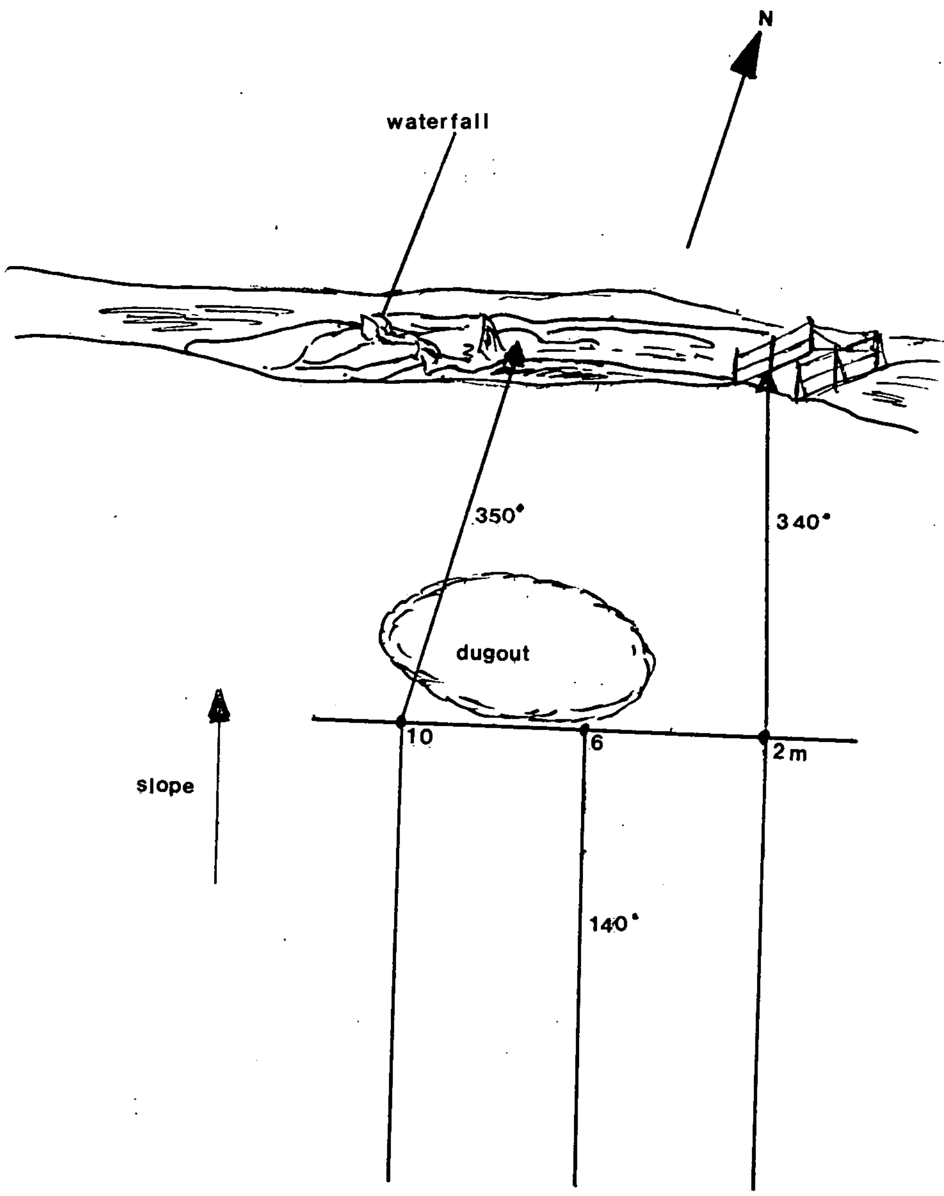


Figure 5.1.3b.1

Plate 5.1.3b.1

Trout Beck

Waterfall & Bridge

Plate 5.1.3b.2

Trout Beck

Dugout Area

5.1.4 *Dryas octopetala*

5.1.4 White Well enclosure on Cronkley Fell in the Upper Teesdale NNR, an SSSI managed by English Nature. In the enclosure the sugar limestone is being eroded, leaving grassy knolls. It is an open site in which there is sparse *Sesleria-Galium* grassland. The National Grid Reference is 35(NY)/839283 the altitude is 536 m. The site was laid out by the method used for the long term monitoring of calcicolous grassland. The plot was not marked with wire loops due to the shallow nature of the soil. Relocation is made from the pattern of boulders and careful photography. (see plates 5.1.4.1, 5.1.4.2, & Fig. 5.1.4.1) The percentage cover of the site by *Dryas octopetala* is estimated.

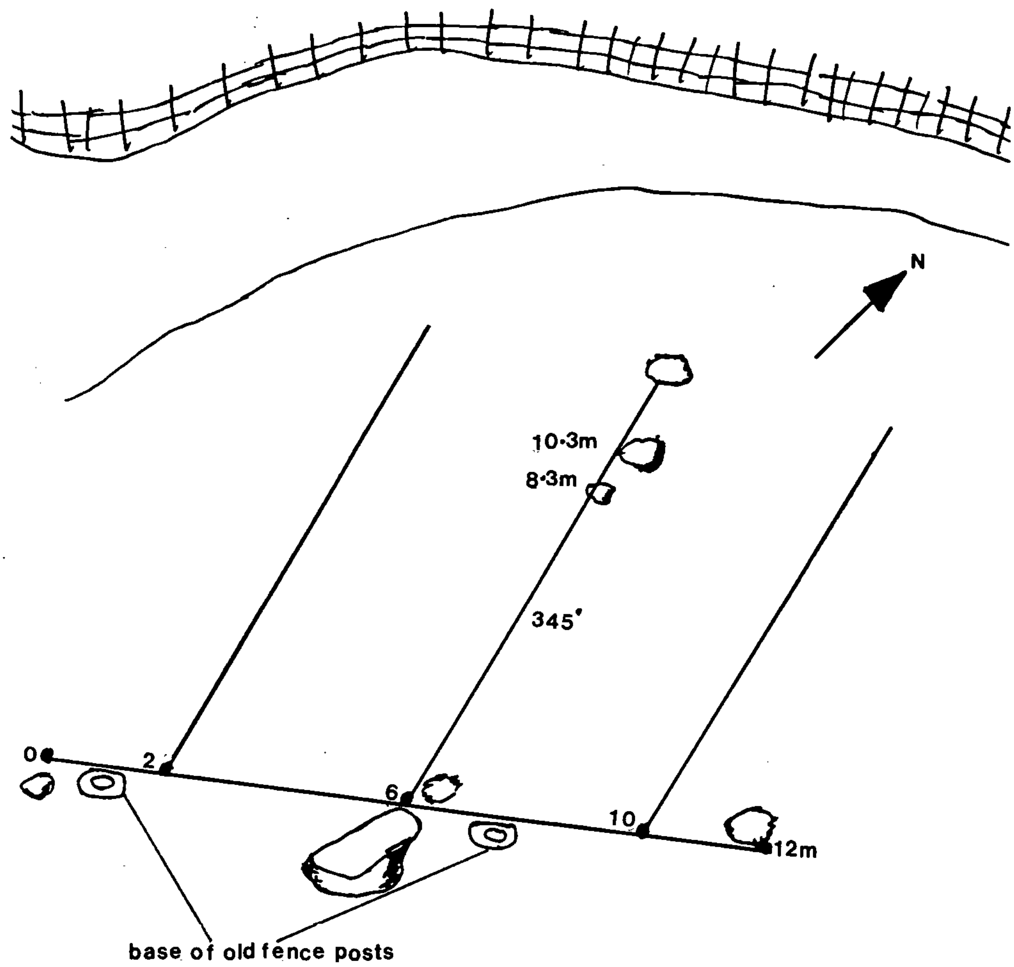


Figure 5.1.4.1

Plate 5.1.4.1

White Well Enclosure

Base Line Tape

Plate 5.1.4.2

White Well Enclosure

Central Tape

10.3 m Stone

5.1.5 *Saxifraga oppositifolia*

Plate 5.1.5.1

Pen-y-ghent Side Cairn

5.1.5a & b Pen-y-ghent side near the Pennine Way. The site is below a cairn (see plate 5.1.5.1) to the north of the Pennine Way on the north side of Pen-y-ghent. The National Grid Reference is 36(SD)/837743 and the altitude 600 m. The ascent was from Horton in Ribblesdale by Horton Scar Lane and Pennine Way until a sign post is reached, then turn to left (see plate 5.1.5.2).

Plate 5.1.5.2

Pen-y-ghent Side Sign Post

The amount of *Saxifraga oppositifolia* was very sparse, the method adopted for recording was to select two areas and to frame these with the 0.5 x 0.5 m quadrat. Photographs were taken of the plants growing within the marked area. In successive years this procedure can be repeated and the growth (coverage) compared. The areas selected are:-

5.1.5a. Growth is on vertical rocky ledges, the plants are growing on the west facing rocks. In near by ledges there were present species of moss, grass and *Asplenium* sp.

5.1.5b. Growth is facing south on the side of the same rocky ledges. In this area the plants were flowering and the growth trailing rather then in crevices. There was no competition from other plants.

5.1.5c Moughton Common, the top of Moughton is mainly grass in which there are large areas of limestone pavement. The site is on a hill side below a scar south of the Ordnance Survey column. (see plate 5.1.5c.1) The National Grid Reference is 36(SD)/785719 and the altitude 370 m. This is an isolated site on a bankside which faces south-west. (see plates 5.1.5c.2, 5.1.5c.3). The area of *Saxifraga oppositifolia* forms a narrow strip. There are no natural landmarks to lay out a site, pegs were placed on the bankside and 0.5 x 0.5 m quadrat used. Photographs were taken showing the position of the peg and the coverage of the area by *Saxifraga oppositifolia* (see Fig. 5.1.5c.1 for quadrat pattern). The area is grazed by sheep. The ascent was made from Wharfe.

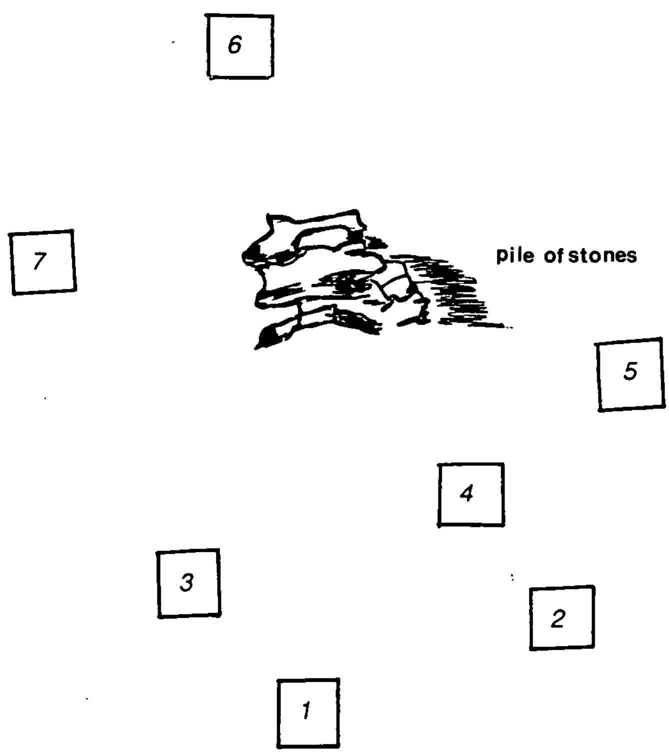


Figure 5.1.5c.1

Plate 5.1.5c.1

Moughton Common

O.S. Column on sky line

Plate 5.1.5c.2

Moughton Common

Site

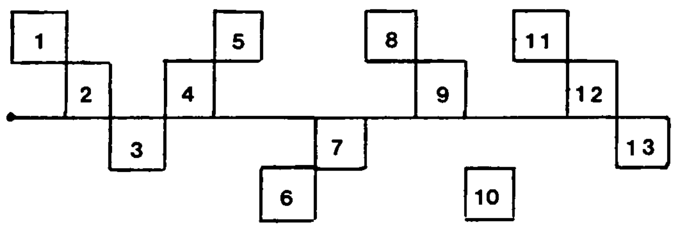
Plate 5.1.5c.3

Moughton Common

Pile of Stones

5.1.5d Brown Cove, Helvellyn this is the site of an old lead mine. The National Grid Reference is 35(NY)/339155 and the altitude is 800 m. The *Saxifraga oppositifolia* is growing on the remains of a refuse tip, "a raw, unleached deposit evidently containing a large amount of calcite. Thickly colonised by *Saxifraga oppositifolia*". (Ratcliffe, 1960) The site on the tip faced north-north-east. The weather conditions were such that on the first visit it was impossible to lay out the site in the method for the long term monitoring of calcicolous grassland, due to an extremely high wind. A tape was laid and the site marked using boulders and rocks for future reference. The percentage cover was recorded using a 0.5 x 0.5 m quadrat as shown in the sampling pattern. A sketch and photographs are used for the relocation of the site. (see plates 5.1.5d.1, 5.1.5d.2, 5.1.5d.3, & Fig. 5.1.5d.1). The area is grazed by sheep.

sampling pattern



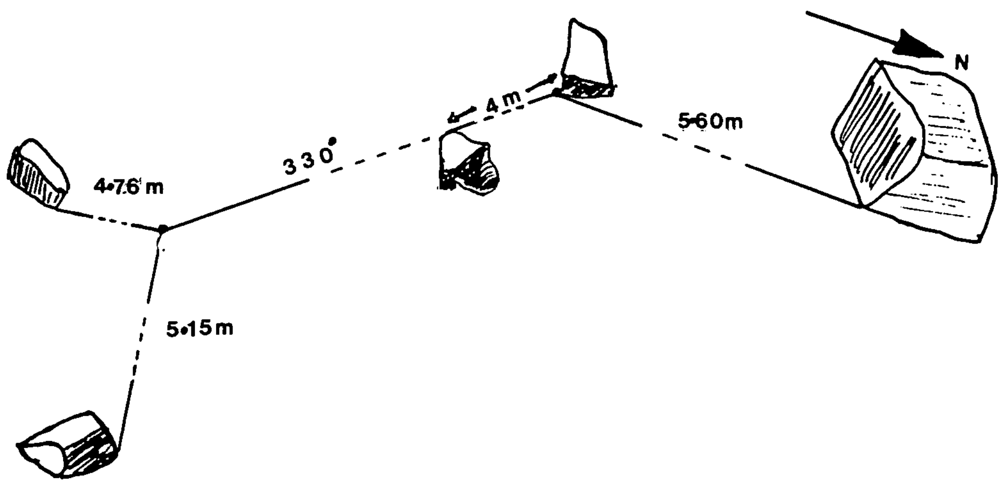


Figure 5.1.5d.1

Plate 5.1.5d.1

Brown Cove

Tape

Plate 5.1.5d.2

Brown Cove

North End of Tape

Plate 5.1.5d.3

Brown Cove

South End of Tape

5.2 Results

5.2.1 *Hymenophyllum wilsonii*

5.2.1a Johnny's Wood see plates 5.2.1a.1 and 5.2.1a.2, showing coverage for 1992 and 1993.

Plate 5.2.1a.1

Johnny's Wood

1992

Plate 5.2.1a.2

Johnny's Wood

1993

5.2.1b Glencoyne Wood see plates 5.2.1b.1 and 5.2.1b.2 for site 5.1.1b in 1993 and plates 5.2.1b.3 and 5.2.1b.4 showing the coverage on the side of Moss Crag in 1992 and 1993.

Plate 5.2.1b.1

Glencoyne Wood

Site 5.1.1b 1993

Plate 5.2.1b.2

Glencoyne Wood

Site 5.1.1b 1993

Plate 5.2.1b.3

Glencoyne Wood

Moss Crag 1992

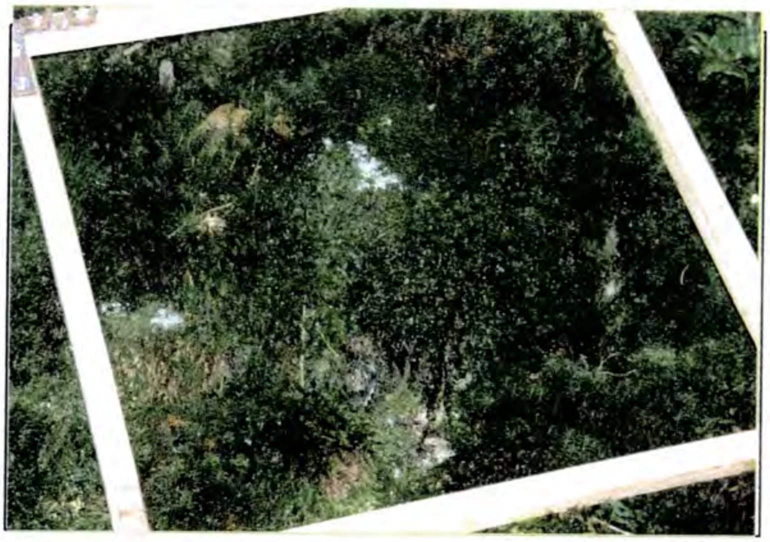


Plate 5.2.1b.4

Glencoyne Wood

Moss Crag 1993

5.2.1c Guerness Gill see plates 5.2.1c.1 and 5.2.1c.2 showing the coverage in 1992 and plates 5.2.1c.3 and 5.2.1c.4 for 1993.

Plate 5.2.1c.1

Guerness Gill

1992

Plate 5.2.1c.2

Guerness Gill

1992

Plate 5.2.1c.3

Guerness Gill

1993

Plate 5.2.1c.4

Guerness Gill

1993

5.2.2 *Draba incana*

5.2.2a Thistle Green: estimated total numbers of plants were:

Year	Plants
1991	3,008
1992	880
1993	1,760

Table 5.2.2a.1

Flowering and non-flowering individuals were recorded separately.

(See Appendix II.a for detailed results.)

5.2.2b Tailbrigg Gill: the plants were sparse, see plates 5.2.2b.1 and 5.2.2b.2 for years 1992 and 1993.

Plate 5.2.2b.1

Tailbrigg Gill

Site 5.1.2b 1992

Plate 5.2.2b.2

Tailbrigg Gill

Site 5.1.2b 1993

5.2.3 *Rubus chamaemorus*

5.2.3a "Moor House": numbers of shoots in the area were:-

Year	Shoots
1991	2,240
1992	3,264
1993	5,168

Table 5.2.3a.1

(See Appendix II.b for detailed results.)

5.2.3b Trout Beck: numbers of shoots in the area were:-

Year	Shoots
1991	2,544
1992	3,440
1993	4,528

Table 5.2.3b.1

(See Appendix II.c for detailed results.)

5.2.4 *Dryas octopetala*

5.2.4 White Well: the percentage cover in the enclosure was estimated to be:-

Year	% Cover
1991	11.86
1992	12.11
1993	13.25

Table 5.2.4.1

(See Appendix II.d for detailed results.)

5.2.5 *Saxifraga oppositifolia*

5.2.5a & b Pen-y-ghent side: for site 5.1.5a compare plates 5.2.5a.1 and 5.2.5a.2 for 1992 and 1993 respectively. For site 5.1.5b compare plates 5.2.5b.1 and 5.2.5b.2 for 1992 and 1993 respectively.

Plate 5.2.5a.1

Pen-y-ghent side

Site 5.1.5a 1992

Plate 5.2.5a.2

Pen-y-ghent side

Site 5.1.5a 1993

Plate 5.2.5b.1

Pen-y-ghent side

Site 5.2.5b 1992

Plate 5.2.5b.2

Pen-y-ghent side

Site 5.2.5b 1993

5.2.5c Moughton Common: see plates 5.2.5c.1 to 5.2.5c.7 for 1993.

Plate 5.2.5c.1

Moughton Common

Peg 1 - 1993

Plate 5.2.5c.2

Moughton Common

Peg 2 - 1993

Plate 5.2.5c.3

Moughton Common

Peg 3 – 1993

Plate 5.2.5c.4

Moughton Common

Peg 4 – 1993

Plate 5.2.5c.5

Moughton Common

Peg 5 – 1993

Plate 5.2.5c.6

Moughton Common

Peg 6 – 1993

Plate 5.2.5c.7

Moughton Common

Peg 7 – 1993

5.2.5d Brown Cove: the estimated percentage cover was:-

Year	% Cover
1992	16.07
1993	21.15

Table 5.2.5d.1

CHAPTER 6

Discussion

The aim of this project was to examine the possible effect of climate change on plants with their southernmost limit in northwest Britain. In carrying out this investigation it was assumed that the geographical range of plants was determined to a considerable extent by the macroclimate (see 2.3).

In obtaining the geographical distribution of the plant species' in Europe certain limitations were experienced. The maps used for the AFE distributions were as published (see 4.1), the maps used to obtain information for the NAFE geographical distributions (see 4.1) are limited in their accuracy. The most accurate information was available for Fennoscandia (Hultén, 1950) and the British Isles (Perring & Walters, 1990) whereas the information for eastern Europe was very limited. In both cases the distribution only recorded presence or absence in the locality and no indication of abundance or continuity.

The environmental data (see 4.1) used for the simulations was not without limitations, not least the use of climatic values estimated for the mean elevation of the 50 km grid squares. More locally, soil moisture estimates could not be made for those areas in Iceland and Svalbard occupied by ice-sheets, and the limited information from high altitude stations in the Azores (see 4.2.4). The response surface gives a visual picture of the climatic space which best fits an individual species. Its value is, however, limited as it does not take into account edaphic factors, nor the interaction with other members of the ecosystem. It does however give a measure of probability of occurrence of the species with any combination of the climatic values.

The simulations for the Pteridophytes (see 3.1) show that most require a climatic space which is humid, all require an AET/PET >0.60 and most also low winter temperatures; the exceptions to the low temperatures are the species of *Hymenophyllum.* The normal simulations show the main regions for their occurrence are in northern and central Europe. The *Hymenophyllum* spp. are the exception, occurring in the extreme western fringes of mainland Europe the British Isles and the Azores. The OSU scenario shows a movement north and eastward, the occurrence.in the British Isles being much reduced. The UKMO scenario shows a continuation of the trend north and east. There are no occurrences in the British Isles, except for *Hymenophyllum* spp. which still occur in the Isles of Scilly and the southwest of Europe.

The distribution maps for Angiosperms (see 3.2) show the normal simulation of the Continental Northern Element (see 2.3) to be mainly a central and northern group, extending in many cases eastward. Where the response surface shows at least two distinct climatic optima the species is simulated in southern Europe. The OSU scenario shows a general movement north and east, those species which are at the present time are occurring in the Iberian Peninsula are now occurring in the southwest of the British Isles. The UKMO scenario shows a reduction in sites selected, and a further trend north and east, in the British Isles, only occurring in Scotland.

The normal simulation for the Northern Montane Element (see 2.3) shows a more northern distribution with scattered occurrences in the higher parts of southern Europe. This widely scattered distribution is seen in the response surfaces. The OSU scenario shows a move northward, with a slight eastward trend, some still in the higher regions of southern Europe. In the British Isles only *Rubus saxatilis* is occurring in England, Wales and Ireland. The UKMO scenario shows a further northeastern drift, the only presence in the British Isles is *Rubus saxatilis* in Scotland.

The Arctic-Subarctic element (see 2.3) shows the normal simulation to have a wider spread in central Europe than occurs. The OSU scenario has a northern move, although still in the Alpine region and in Scotland. In the UKMO scenario it is greatly reduced, spreading further north, but still in the Alps.

The Arctic-Alpine Element (see 2.3) is the largest group of plants and typically the response surfaces shows at least two climatic optima, arctic and alpine. The response surfaces show this group to all require an AET/PET >0.75 confirming their ability to tolerate high atmospheric humidity. The normal simulation shows some variance in the alpine region in many cases a reduction in numbers, this could be due to the fact that many grow at high altitude. The OSU scenario shows that in most cases the plants have migrated north and their presence in southern Europe is greatly reduced. In the British Isles most are only present in Scotland, but where their present distribution shows them in the Iberian Peninsula they have migrated to southern England, Ireland and Wales. The UKMO scenario shows a further reduction in numbers and the move northwards is continued with few present in southern and central Europe. In the British Isles there are a small number of species present in Scotland.

The two GCM scenarios cited above OSU (Schlesinger & Zhao, 1989) with a 2.8°C rise in global mean temperature and 8% increase in precipitation, and the UKMO (Mitchell, 1983) with a 5.2°C increase in global mean temperature and 15% increase in precipitation, are based on what might happen. There is no certainty about the future climate change, and the figures given are for global change and it is now known that regional variations are occurring (see 2.4).

The potential impact upon the species studied shows a reduction in their range, a general trend north and east, also a reduction in numbers, many no longer present in the British Isles. The migration of species due to changes in climate has occurred previously (Huntley, 1991) but never at the rate which will be necessary if changes occur on a time scale suggested by the GCM (see 2.4). The species are unlikely to be able to migrate by keeping in equilibrium with the climate and genetic change will be too slow. Where overlapping occurs between the present and potential ranges the species is likely to succeed but where there is no overlap it is almost certain to become extinct. The group of species most likely to migrate successfully are the Pteridophytes as the spores are light and wind dispersed (see

3.1). The Angiosperms require an agent for pollination (see 3.2) and many of the species studied are pollinated by insects. We do not know how these pollinators will be affected by the climatic change. Seeds require dispersal and are unlikely to be carried the distances necessary for new populations to become established. Those species which are long established and able to survive in changed climatic conditions will be subject to competition from other species which are migrating into their location.

The sites selected for monitoring species (see 5.0) were chosen, where possible, to obtain differing environmental conditions. The sites for *Hymenophyllum wilsonii* 5.1.1a, 5.1.1b, and 5.1.1c are in woodland, 5.1.1d is by the side of a stream. The site for *Draba incana* 5.1.2a is an area of blown out sugar limestone, and 5.1.2b is a grassy limestone cliff at a lower altitude. The sites for *Rubus chamaemorus* are in close proximity 5.1.3a is relatively flat whereas 5.1.3b is on a slight slope. Four sites have been selected for *Saxifraga oppositifolia*; 5.1.5a and 5.1.5b are on the same rocky ledges but have differing aspects, site 5.1.5c is on a grassy bankside amongst limestone rocks, and site 5.1.5d is on the site of an old lead mine refuse tip. By varying the sites it should be possible, in time, to record the changes in growth patterns in the differing microclimates.

In the time span of this investigation no significant changes can be recorded in the growth patterns of the species selected for monitoring. *Draba incana* Thistle Green site 5.2.2a shows variation which accords with previous studies of the species in Upper Teesdale (Bradshaw & Doody, 1978). There is also a notable increase in numbers of *Rubus chamaemorus* shoots, 5.2.3; later counts were made following a number of dry seasons, which were followed by wet seasons. This could have affected the water potential deficit (see 3.2.8) and caused the increased number of shoots.

In conclusion this investigation shows that many of the plants growing at their southernmost limit in northwestern Britain are in danger of becoming extinct.

Some of the species which occur on the Iberian Peninsula could in theory migrate to the southwest of the British Isles. The investigation has concentrated on increased temperature and has not considered the effect of other factors on the physiology of plants. Photosynthesis and plant productivity may be effected by the increase in CO_2, and photoperiodism by change in latitude. The probable change in precipitation patterns could effect drought sensitive species. Mooney & Billings (1961) made a detailed comparison of arctic and alpine populations of *Oxyria digyna* and found that the plants had adapted genetically to arctic conditions, but were unable to say how long was needed for this to occur. The evidence available from the studies of previous periods of climatic change suggest that in the present circumstances the changes will be too rapid for genetic adaptation of the threatened species.

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APPENDIX I

Recording Method for long term monitoring of calcicolous grasslands.

Equipment required, four tapes 12 m in length marked at 0.5 m intervals, tent pegs to hold the tapes in position, two measuring tapes, a trowel, insulated copper loops approximately 10 cm, a quadrat frame 1.0 x 0.5 m divided into 0.5 x 0.5 m sections, a metal detector, a camera, a compass and an Ordnance Survey map of the area.

A 12 x 12 m grid is laid out with tapes so that the quadrats can be positioned rapidly. The position of the grid, where possible, is marked permanently with seven loops of insulated copper wire, buried 10 cm in the ground which can be relocated using a metal detector. The markers are placed in such a position (see Fig. A1.1) that the plot can be relocated even if only two markers remain.

The recording is made using 36 0.5 x 0.5 m quadrats (0.25 m^2) (see Fig A1.1) Each plot is divided into four 6 x 6 m blocks, each block is subdivided into nine 2 x 2 m units. Each 2 x 2 m unit is sampled by a 0.5 x 0.5 m quadrat located in one of 16 positions.(see Fig A1.2) The same sampling pattern is used for each plot.

The grid when laid out has tapes marked at 0.5m intervals, along at least one border of each block. The quadrat frame is oblong, 1 x 0.5 m, and is divided into two 0.5 x 0.5 m quadrats. The quadrat to be sampled in any of the 2 x 2 m units can be located by positioning the frame at the appropriate mark on the tape, or, by flipping the frame over once from the nearest mark.

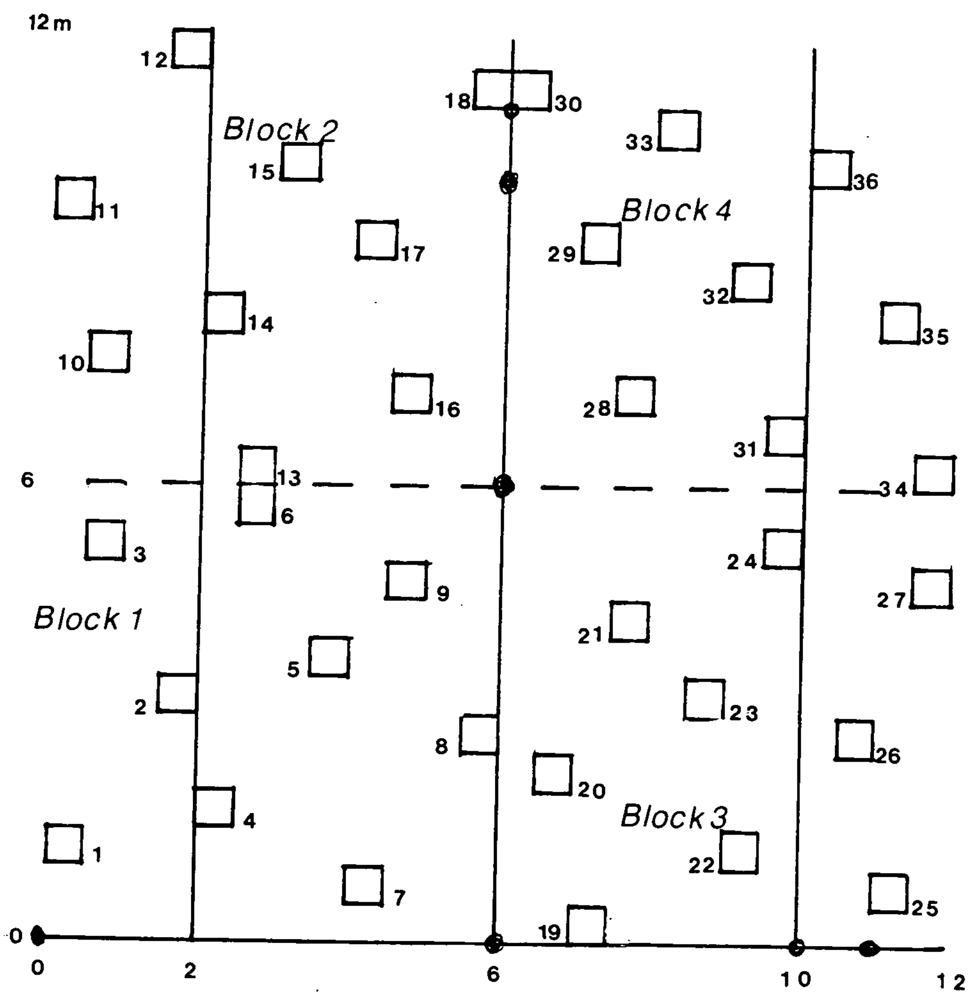
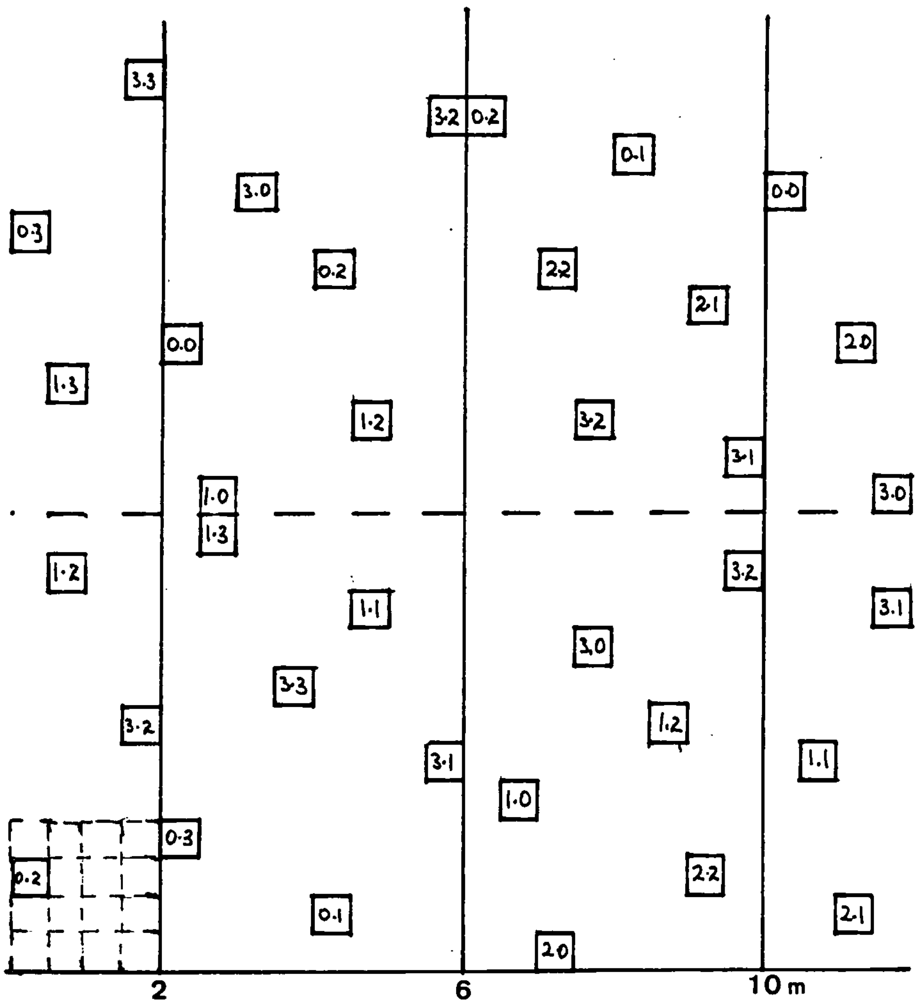


Figure A1.1 Layout of the quadrats in a plot.

The solid black lines show the positioning of the tapes used to mark the plot for random sampling. The circles indicate the positions of the permanent copper marker loops.



0·3	1·3	2·3	3·3
0·2	1·2	2·2	3·2
0·1	1·1	2·1	3·1
0·0	1·0	2·0	3·0

Figure A1.2

Details of the 16 positions in the 2 x 2 m units

APPENDIX II

II.a *Draba incana* Thistle Green, Cronkley Fell.

Counts of numbers of individuals in 0.5 × 0.5 m quadrats.

Year	1991		1992		1993	
Quadrat	flowering	vegetative	flowering	vegetative	flowering	vegetative
1	1	1	0	0	1	7
2	0	11	0	1	0	9
3	0	0	0	1	0	0
4	0	7	0	3	0	5
5	0	0	0	0	0	0
6	0	3	0	6	0	2
7	0	6	0	0	0	5
8	2	18	0	10	0	1
9	0	0	0	0	0	0
10	0	3	0	2	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	1	5	0	0	0	0
14	0	0	0	0	0	0
15	1	29	1	2	0	0
16	0	1	0	0	0	0
17	0	0	0	0	0	0
18	1	26	0	11	2	18
19	4	8	0	3	0	3
20	0	0	0	2	0	6
21	0	1	0	1	0	0
22	0	20	0	2	0	3
23	0	10	0	2	0	9
24	0	2	1	0	0	0
25	0	0	0	0	0	6
26	0	2	1	4	3	9
27	0	2	0	0	0	1
28	0	1	0	1	0	1
29	0	2	0	0	0	0
30	0	15	0	1	2	13
31	0	0	0	0	1	3
32	1	0	0	0	0	0
33	0	4	0	0	0	0
34	0	0	0	0	0	0
35	0	0	0	0	0	0
36	0	0	0	0	0	0
Totals	**11**	**77**	**3**	**52**	**9**	**101**

Note: All individual plants showing flowers, flower buds or fruiting are recorded as flowering plants.

The plot was not marked out with wire loops due to the shallow nature of the soil.

II.b *Dryas octopetala* White Well enclosure, Cronkley Fell.

Quadrat	Percentage Cover		
	1991	1992	1993
1	0	0	0
2	0	0	0
3	0	1	0
4	0	0	0
5	0.5	2	6.25
6	3	35	50
7	30	30	33.3
8	2	0	0
9	0	0	0
10	0	0	0
11	15	0	0
12	0	0	0
13	1	25	25
14	0	0	0
15	40	0	0
16	99	40	50
17	80	35	50
18	0	0	0
19	0	0	0
20	80	85	90
21	0	0	0
22	0	0	0
23	0	0	0
24	0.5	2	12.5
25	0	11	0
26	0	0	0
27	0	0	0
28	1	90	90
29	0	0	0
30	0	0	0
31	40	70	45
32	0	0	0
33	0	0	0
34	0	0	0
35	0	0	0
36	35	10	25
Overall percentage cover	**11.86**	**12.11**	**13.25**

Note: The plot was not marked out with wire loops due to the shallow nature of the soil.

II.c *Rubus chamaemorus* Moor House

Quadrat	Number of shoots 1991	1992	1993
1	3	3	7
2	4	3	11
3	8	7	6
4	3	8	12
5	3	4	0
6	2	3	5
7	0	4	2
8	0	0	5
9	3	4	9
10	7	5	10
11	7	6	10
12	3	7	8
13	0	4	2
14	9	12	8
15	9	8	8
16	1	0	7
17	7	11	4
18	7	3	5
19	4	4	4
20	0	3	11
21	0	4	12
22	3	0	8
23	2	4	13
24	4	8	12
25	2	6	8
26	5	7	8
27	6	3	13
28	1	0	11
29	4	6	17
30	4	0	6
31	8	5	9
32	3	16	14
33	3	5	13
34	5	12	21
35	7	17	8
36	3	12	16
Totals	**140**	**204**	**323**

II.d *Rubus chamaemorus* Trout Beck

Quadrat	Number of shoots 1991	1992	1993
1	5	7	9
2	5	6	6
3	3	6	10
4	11	16	15
5	14	15	10
6	9	11	16
7	0	4	18
8	3	6	7
9	10	5	6
10	4	0	2
11	3	5	8
12	8	8	13
13	8	6	20
14	10	4	3
15	1	10	4
16	12	3	5
17	4	10	9
18	1	7	8
19	6	7	10
20	0	2	11
21	3	9	7
22	2	2	5
23	3	4	10
24	1	2	9
25	3	1	4
26	5	9	7
27	3	2	6
28	1	9	6
29	8	0	2
30	3	5	6
31	4	4	6
32	0	8	3
33	1	7	6
34	0	6	8
35	5	9	6
36	0	0	2
Total	159	215	283

II.e Saxifraga oppositifolia Brown Cove

Quadrat	Percentage cover	
	1992	1993
1	20	25
2	15	18
3	8	12
4	15	20
5	50	60
6	40	50
7	15	25
8	15	20
9	20	30
10	0	5
11	1	5
12	10	4
13	0	1
Overall Percentage cover	**16.07%**	**21.15%**