Past forests of Europe

H. J. B. Birks, W. Tinner

European forests have varied in their composition, structure, and extent over the last 5 million years or more in response to global climate changes. European forests have also undergone very major changes due to the alternating glacial-interglacial cycles of the Quaternary (last 2.6 million years). European forests have greatly changed in their extent and structure in the last 5000 years due to human activities (the Homo sapiens phase) in the current Holocene interglacial in which we live. Contemporary ecologists and foresters can learn from ‘lessons from the past’ about forest responses and resilience to environmental changes in the past.

Introduction

Were European forests 500, 5000, 15000, 150000, 1.5 million, 2.5 million, and 5 million years ago similar in species composition, structure, and extent to the forests of Europe today? As we cannot directly observe the forests of the past, to answer these questions we need to reconstruct past forests indirectly using the fossil record. This involves the study of seeds, fruits, leaves, wood, and charcoal (macrofossils) and of microscopic pollen grains, spores, cells (e.g. stomata), and charred particles (microfossils) preserved in lake, bog, alluvial, and other sediments where organic material can be preserved. Pollen analysis as a tool for vegetation reconstruction - invented in 1916 by the Swedish geologist Lennart von Post - was and still is the dominant technique in the Quaternary period, especially the last 15000 years of the late-Quaternary. Von Post had the idea of expressing fossil pollen assemblages as percentages of the sum of pollen grains counted, and of presenting these percentages as stratigraphical pollen diagrams with pollen assemblages plotted against their stratigraphical position through the sediment sequence (Fig. 1). He showed strong similarities in pollen diagrams from a small area, and striking differences between different areas. He was thus able to provide the dimension of time (vegetation’s fourth dimension) to the study of past vegetation and forests.

Pollen analysis

There are ten basic principles of pollen analysis (see Box 1). The results of a pollen analysis are most commonly presented as a pollen diagram, showing how the percentages of different pollen types vary with depth, and hence age, in the sedimentary sequence (Fig. 1). When many sequences have been studied, their pollen data can be mapped for a particular time interval (e.g. 5000 years ago) to produce so-called ‘isopollen’ maps for particular pollen types where the contours represent different pollen values (e.g. 2.5%, 5%, 10%) (Fig. 2). Alternatively when interest is centred on the directions and rates of tree spreading, so-called ‘isochrone’ maps can be constructed where the contours represent ages established by radiocarbon dating (e.g. 5000, 6000, 7000 years ago). When the value of a particular pollen type exceeds a certain threshold value it can be interpreted as reflecting the first expansion of that taxon at different sites (Fig. 3). The first arrival of a taxon is more difficult to assess, because the absence of pollen or macrofossils may not mean a true absence of the taxon in the landscape. Interpretation of pollen-stratigraphical data in a qualitative manner in terms of major past vegetational changes is relatively straightforward. Quantitative interpretation of such data in terms of quantitative estimates of past plant abundances is less straightforward because of the differential production, dispersal, and hence representation of different pollen types. Approaches for quantitative interpretation are currently an area of active research within Europe and elsewhere.

Fig. 1: Summary pollen diagram from Loch Cill an Aonghais (Argyll), a small lake in south-west Scotland covering the last 12000 radiocarbon years. The horizontal lines represent partitions of the pollen stratigraphy into pollen assemblage zones. The vertical axis is radiocarbon (14C) years before present (BP) based on eight radiocarbon dates. The small arrows by the Betula (birch), Quercus (oak), Alnus (alder), and Corylus/Myrica (hazel/bog myrtle) indicate where these trees or shrubs are inferred to have first expanded near this site. Cryocratic taxa are coloured red and stippled. These taxa become abundant again in the open conditions of the Illinoian sapropods phase where they are shown in plain red. Proteocratic taxa are coloured blue. Mesocratic taxa are green. Diageneric and palaeoboreal taxa are orange, and taxa associated with human activity and the Illinoian sapropods phase of the Holocene are shown in red. All the pollen and spore percentages are expressed as percentages of the total number of terrestrial pollen and spores counted (generally 500-600 per sample). Pollen analyses by Sylvia M. Peglar.

Fig. 2: ‘Isopollen’ maps of Quercus (oak) pollen percentages across Europe for 12000, 10000, 8000, 6000, 4000, and 2000 radiocarbon years before present (BP). Note the progressive northward spread into southern Scandinavia by 8000 BP and the subsequent contraction at 2000 BP in Norway. The percentage contours are percentages of total tree and shrub pollen. (Modified from van der Bilt et al.14)
Box 1: Principles of pollen analysis

- Pollen grains and spores are produced in great abundance by plants
- A very small fraction of these fulfil their natural reproductive function of transferring the male gamete to the female ovary: the vast majority fall to the ground
- Pollen and spores decay more or less rapidly, unless the processes of biological decomposition are inhibited by a lack of oxygen, such as in bogs, lakes, and the ocean floor where pollen is preserved
- Before reaching the ground, pollen is well mixed by atmospheric turbulence, which results in a more or less uniform pollen rain within an area of similar vegetation and landform
- The proportion of each pollen type depends on the number of parent plants and their pollen productivity and dispersal. Hence the pollen rain is a complex function of the composition of the vegetation. A sample of the pollen rain is thus an indirect record of the regional vegetation at that point in space and time
- Different pollen grains and spores can be identified to various taxonomic levels (e.g., species, genus, family)
- In vegetated areas pollen is ubiquitous in lake and bog sediments. Very high concentrations (usually around 100,000 cm⁻¹) in the sediment permit efficient analyses and statistically robust results (standard pollen counts are usually ca. 300-1000 grains per sample)
- If a sample of the pollen rain is examined from a peat or lake-mud sample of known age (dated by annual layers or radiocarbon dating), the pollen assemblage is an indirect record of the regional and local vegetation surrounding the sampled site at a point in space and time
- If pollen assemblages are obtained from several levels through a sediment sequence, they provide a record, admittedly an indirect record, of the regional and local vegetation and their development in the sampled area at various times during the time interval represented by the sedimentary record (Fig. 3)
- If two or more pollen assemblages are obtained from several sites, it is possible to study changes in past pollen assemblages and hence in the regional and local vegetation through both time and space (Figs. 2 and 3)

Knowledge of the Flora and vegetation of the Palaeoegen and Neogene (Arcto-Tertiary) and the Quaternary (Tertiary) periods (Fig. 1 for an outline of the relevant geological time scales) is very fragmentary due to the shortage of fossiliferous sedimentary sequences in Europe. Following the tropical and sub-tropical Palaeocene, Eocene, Oligocene, and Miocene epochs (165-5.3 million years ago) when plants (e.g., Alpia palma) found today in the tropical lowlands of the Indo-Malaya region occurred in north-west Europe, the European tree flora of the Pliocene epoch (5.3-2.6 million years ago) contained many genera characteristic of the modern European forests (e.g., Quercus oak, Carpinus hornbeam, Fagus beech, Pinus pine, Prunus plum, Alnus alder, Sequoia redwood, Taxodium cypress, Magnolia magnolia, Carya hickory, Carya pecan, paper birch, Engelhardia, Aesculus chestnut). These trees belong to the so-called Arcto-Tertiary geoflora that in the Neogene existed widely in the Northern Hemisphere across North America, Europe, and Asia. This geoflora was first defined by J.S. Gardner and C. Ethington in 1869. The successive loss of this flora during the Pliocene and Pleistocene and its replacement by the flora of the Quaternary and their restriction today to two almost opposite areas of the globe (eastern Asia and eastern North America) is explained by the hypothesis explicitly presented in the 1850s by the American botanist Asa Gray (1818-1888). The cool phase within the late Pliocene epoch and the subsequent Pleistocene continental glaciations, combined with the glacial chains of glacialized mountains (e.g., Pyrenees, Alps, Carpathians, Caucasus mountains) and the Mediterranean Sea provided barriers to the southward retreat of many of the Arcto-Tertiary geoflora resulting in their progressive extinction in Europe. In contrast, the mountain chains and valleys of south-eastern Asia (e.g. Hymalaya and North America (e.g., Appalachian, Rocky Mountains) run north-west to south-east or north to south reaching low latitudes without sea barriers, thereby permitting temperate and warm temperate trees to spread southward along unglaciated areas or valley corridors in cold stages and to spread northward during temperate intervals. As a result of the west-end barriers and the relatively cold stages in the late Pliocene and early Pleistocene, Europe lost many trees or their close relatives that today are found in the temperate-subtropical ‘evergreen forest’ of south-eastern China. These were largely replaced by trees of the temperate ‘mixed mesophytic forest’. Many taxa had already disappeared at the beginning of the Quaternary (e.g., Liquidambar, Meliosma, Pseudolarae falcon larch, Stenopteris), while others survived longer (e.g., Liquidambar, Magnolia, Taxodium, Sequoia, Pseudolarix, coniferous, and possibly Larix larch) in such microrefugia during the LGM, along with Pinus pine, and possibly Alnus alder, Populus aspen, and Ulmus elm, both now found in the north-eastern parts of the Siberian-Himalayan region and the Tibetan highlands in Kazakhstan. Trees may also have occurred scattered in low and moist sites (water seepages, ravines), so-called ‘cryptic’ or ‘micro’ refugia in the Mediterranean Sea. These trees such as Pinus pine, and Larch larch may have grown locally in such miresequarengina during the LGM, along with Betula birch, Salix willow, and possibly Alnus alder, Populus aspen, and Ulmus elm, both now found in the north-eastern parts of the Siberian-Himalayan region and the Tibetan highlands in Kazakhstan.

1. A common problem is that of the late-glacial vegetation in the European forests of the Quaternary period. The Quaternary period (last 2.6 million years) was characterized by widespread and repeated interglacial and interglacial stages, the last being about 2.6 million years ago. What were European forests like prior to the Quaternary?

Europe's forests during the Quaternary interglacial stages

Pollen analysis and macrofossil studies reveal that in north-western and central Europe there is strikingly similar vegetation development from the end of a glacial stage through the ensuing interglacial (about 10,000-15,000 years duration) and into the next glacial stage. The exact nature and extent of these repeated long glacial-stage conditions and where did they grow in the glacial stages?

The evidence we have suggests that many European trees survived the last glacial maximum (LGM) in relatively narrow refugial elevational belts (ca 500-800m) in the mountains of southern Europe (including the Caucasus) and possibly in parts of western Asia. These belts lay between lowland xeric, steppe-like vegetation too dry for tree growth and high-elevation tundra-like vegetation, or permanent snow or ice, too cold for tree growth. Such mid-elevation belts of trees can be seen today in the Andes, Asian Alps, Rocky Mountains, the eastern parts of the Siberian-Himalayan region, and the Tibetan highlands in Kazakhstan. These belts lay between lowland xeric, steppe-like vegetation too dry for tree growth and high-elevation tundra-like vegetation, or permanent snow or ice, too cold for tree growth. Such mid-elevation belts of trees can be seen today in the Andes, Asian Alps, Rocky Mountains, the eastern parts of the Siberian-Himalayan region, and the Tibetan highlands in Kazakhstan.

There is increasing evidence from macrofossils and charcoal remains in central, eastern, and north-eastern Europe that conifer trees such as Pinus pine, and Larch larch may have grown locally in such miresequarengina during the LGM, along with Betula birch, Salix willow, and possibly Alnus alder, Populus aspen, and Ulmus elm, both now found in the north-eastern parts of the Siberian-Himalayan region and the Tibetan highlands in Kazakhstan.

At the end of an interglacial, the temperature and moisture rise and the protocyclic phase begins. Base-demand shade-intolerant herbs, shrubs, and trees (e.g. Betula, Salix, Populus, Picea, Juniperus juniperus, Sorbus aucuparia rowan) immigrate into formerly glaciated areas and expand to form a mosaic of grassland, scrub, and open woodland growing on unglaciated, fertile soils rich in nitrogen and phosphorus and with a low humus content (Fig. 1). The mesotrophic phase is characterised by the development of temperate deciduous forests of Quercus, Ulmus, Tilia lime, Corylus hazel, Fraxinus ash, and Alnus on fertile brown-earth soils (Fig. 1). Shade-intolerant herbs and shrubs are rare as a result of competition and habitat loss, except in openings caused by fire, wind-throw, and, possibly, grazing megaherbivores. The next phase, the oligotrophic phase, comprises open conifer-dominated woods (Pinus pine, Picea, Abies, ericaceous heaths, and bog vegetation) growing on infertile glacial drift and fen peat soils. The coniferous woods contain birch, pine, willow, and possibly Alnus alder, Populus aspen, and Ulmus elm, both now found in the north-eastern parts of the Siberian-Himalayan region and the Tibetan highlands in Kazakhstan. These belts lay between lowland xeric, steppe-like vegetation too dry for tree growth and high-elevation tundra-like vegetation, or permanent snow or ice, too cold for tree growth. Such mid-elevation belts of trees can be seen today in the Andes, Asian Alps, Rocky Mountains, the eastern parts of the Siberian-Himalayan region, and the Tibetan highlands in Kazakhstan.

The protocyclic phase is characterised by the development of temperate deciduous forests of Quercus, Ulmus, Tilia lime, Corylus hazel, Fraxinus ash, and Alnus on fertile brown-earth soils (Fig. 1). Shade-intolerant herbs and shrubs are rare as a result of competition and habitat loss, except in openings caused by fire, wind-throw, and, possibly, grazing megaherbivores. The next phase, the oligotrophic phase, comprises open conifer-dominated woods (Pinus pine, Picea, Abies, ericaceous heaths, and bog vegetation) growing on infertile glacial drift and fen peat soils. The coniferous woods contain birch, pine, willow, and possibly Alnus alder, Populus aspen, and Ulmus elm, both now found in the north-eastern parts of the Siberian-Himalayan region and the Tibetan highlands in Kazakhstan. These belts lay between lowland xeric, steppe-like vegetation too dry for tree growth and high-elevation tundra-like vegetation, or permanent snow or ice, too cold for tree growth. Such mid-elevation belts of trees can be seen today in the Andes, Asian Alps, Rocky Mountains, the eastern parts of the Siberian-Himalayan region, and the Tibetan highlands in Kazakhstan.
The characteristic trees of the interglacial phases differ in their reproductive and asocial properties and ecological and competitive tolerances\textsuperscript{17-19}. Protocretaceous trees have high reproduction rates, low competitive tolerances, high rates of population increase, and display pioneer and “exploitation” traits\textsuperscript{17-18}. Mesocratic trees have low reproduction rates, high competitive tolerances, medium-low rates of population increase, arbuscular phosphorus-scavenging mycorrhiza, and “late-successional,” “competitive,” and “saturation” traits\textsuperscript{17-18}. Oligocretaceous and telocratic trees have medium reproductive rates, high competitive tolerances, medium-low rates of population increase, ectomycohiza with a phosphorus-mining strategy, and “cold-stress tolerant” and “adversity” traits\textsuperscript{17-18}.

Within these three broad groups of protocretaceous, mesocratic, and oligocretaceous and telocratic plants, the actual floristic and forest composition varies from interglacial to interglacial in north-western and central Europe\textsuperscript{58}. Factors such as location of refuge in the cryocratic phase, rates of spreading, distances over which spread occurred, competition, predation, genotypic variation, and chance as it affects survival, dispersal, and establishment may all have contributed to the observed differences in interglacial forest patterns\textsuperscript{58}. Similar cycles occurred in southern Europe, yet with substantial differences in comparison to central and north-western Europe\textsuperscript{58-60}.

Due to warmer conditions, European tree species persisted locally, although strongly reduced, in the steppe-like environment of the interglacial phases. This corresponds to the cryocratic phase in central and northern Europe. At the onset of an interglacial, corresponding to the protocretaceous phase in central and north-western Europe, temperate taxa (e.g. deciduous Quercus, Ulmus, Ostrya, hop-hornbeam, Carpinus) form open forests together with evergreen broad-leaved trees (e.g. Quercus ilex holm oak, Olea europaea olive) and Mediterranean shrubs (e.g. Pistacia pisiachial), while boreal and steppe vegetation declines (e.g. Betula, Juniperus, Artemisia wormwood). Chamaecyparis gooseneckii disappeared in this phase during the mid-interglacial, corresponding to the mesocratic phase in central and north-western Europe, warm-temperate and Mediterranean conifers (e.g. Abies, Pinus) expand into the boreal, deciduous and broad-leaved evergreen forests and arborescent cover increases, probably in response to rising moisture availability. Towards the end of the interglacial, corresponding to the oligocretaceous phase in north-western and central Europe, moisture-loving taxa such as Fagus, Alnus, and Abies gradually replace Mediterranean evergreen broad-leaved trees, while broad-leaved deciduous trees remain important\textsuperscript{61-62}.

Finally, forest cover declines and steppe-like environments expand during the climatic deterioration at the transition from the interglacial to the next glacial (temperature decreases, reduced moisture), corresponding to the telocretaceous phase. There is an apparent order within interglacial forest patterns when viewed at the broad scale of an early interglacial cycle of 10,000-15,000 years, whereas within each phase of an interglacial (ca. 5,000 years) there is often great variation between interglacials, hence the ability of pollen stratigraphy to differentiate between many of the different interglacials\textsuperscript{63}.

Europe’s forests in the Holocene (11,700 years ago–today)

The mesocratic phase in the Holocene interglacial stage was greatly modified about 5,000-6,000 years ago by the onset of forest clearance and prehistoric shifting cultivation and livestock farming (Fig. 1). This new phase, unique to the Holocene is called the Homo sapiens phase (see Box 2\textsuperscript{18}). There was a steep fall in Ulmus pollen values (Fig. 1), probably as a result of an interaction between prehistoric human activities and a tree pathogen, with elm pollen values halving within 5 years at a site in southern England\textsuperscript{64}. Similarly, 5,000–6,000 years ago Abies disappeared from the Mediterranean and sub-Mediterranean lowlands of the Italian Peninsula, probably in response to excessive Neolithic disturbance by fire and by browsing\textsuperscript{65-66}. As with Ulmus in England, Abies collapses were rapid, with pollen values of Abies halving within 13 and 22 years at sites in Italy\textsuperscript{67} and Italian Switzerland\textsuperscript{68}, respectively.

In some areas of central and north-west Europe, forest clearance and largescale deforestation may have facilitated local colonisation and expansion of new immigrants such as Fagus sylvatica European beech, Picea abies Norway spruce, and possibly Carpinus betulus European hornbeam\textsuperscript{69}. While the establishment of Fagus and Picea in warming Merisolic times followed climate change (cooling and a moisture increase) in southern and southern-central Europe\textsuperscript{69-70}, it is possible that the rapid spread of Fagus across central Europe in the last 4,000-5,000 years may have only been facilitated by the creation of abundant, large clearings within Tilia- or Quercus-dominated forests on well-drained soils. In some areas mixed Fagus-Ilex holly-Quercus forests developed whereas in other areas there was a rapid change from Fili- or Quercus dominance to Fagus-dominance\textsuperscript{71}. These changes commonly occurred after an extensive phase of human activity involving clearance and grazing, followed by the abandonment of cleared and cultivated areas. This abandonment may have occurred as a result of local population collapse following, for example, climate change, emigration, or over-exploitation of environmental resources\textsuperscript{71}.

Other types of secondary woodland developed in areas beyond the natural geographical range of Fagus, for example woods of pure Fraxinus excelsior European ash, Quercus spp., Taxus baccata common holly became established on particular soil types following abandonment of cleared or cultivated areas, relaxation in grazing pressure, or reduction in fire frequency\textsuperscript{72}.

The westward, northward, and southward spread and expansion of Picea abies through Finland, Sweden, and Norway over the last 6,000-7,000 years\textsuperscript{73} may be a contemporaneous response to subtle step-wise climate change, a delayed migration unrelated to simple climate change, a response to forest disturbance creating gaps for colonisation, or a combination of these factors\textsuperscript{73}. Whatever its causes, the invasion of Picea into northern and central Fennoscandia over the last 6,000-7,000 years resulted in major changes in forest composition and structure and in soil conditions, with widespread accumulation of mor humus, soil leaching, and podsolisation and changes in the natural fire regime within the boreal forest\textsuperscript{73,74}.

Box 2: Glacial-interglacial phases in north-west Europe

The glacial-interglacial cycle showing the broad changes in biomass, soil, and temperature that take place during a glacial (cryocratic) stage and associated interglacial stage. The phases of the interglacial (protocretaceous, mesocretaceous, oligocretaceous, and telocretaceous) are shown along with the dominant soil features.

Cryocratic:
- glacial stage
- sparse assemblages of pioneer, arctic-alpine, steppe, and ruderal plants
- skeletal mineral soils

Protocretaceous:
- early interglacial stage
- rich assemblages of herbs, shrubs, and trees (b Birch, pine, willow)
- unpatched fertile soils

Mesocretaceous:
- mid interglacial stage
- temperate deciduous forests
- fertile brown-earth soils

Oligocretaceous & Telocretaceous:
- late interglacial stage
- open conifer (spruce, pine), encarcaceae heaths, bogs
- infertile, hum-rich podsol soils and peats

Unique to the Holocene

Home sapiens:
- mid late-Holocene (6,000 years ago-present)
- forest clearance, agriculture
- range of soil types, often fertilised

Box 3: Palaearctic model comparison: past, present and future Mediterranean vegetation

Simulation of future vegetation dynamics at Lago di Massaciuccoli, a coastal lake in Tuscany (central Italy), with a dynamic vegetation model (LANDCLIM) for different climatic conditions (today vs. warming) and levels of disturbance (low vs. moderate). The mid- to late-Holocene (5,000-3,000 years) vegetation type under current climate with moderate land use. Solid lines represent forest composition with moderate land use. Fertile soils, high N & P Base-rich infertile soils More fertile solis, increasing N & P Decreasing temperature

Figure 3 from Ineke et al.\textsuperscript{69}
However, increased human interference including regular burning and wood- and scrub-pasture and hazel coppice expanded during the late Neolithic, Bronze Age, Iron Age.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.

We see that European forests have been changing since the Quaternary (Pleistocene, Holocene) and the realised environmental niches of species been significantly maintained itself in the past 12,000 years.

Effective forest systems of today have a finite time limit to growing due to atmospheric circulation involving climatic shifts that led to terrestrial systems arising at approximately the same time in different parts of the earth system may be accompanied by widespread ecosystem legacies of societal activities can be deciphered, quantified, and used as a key to the understanding of the biotic effects of future environmental change.

Alkenen are commonly used to produce palaeo-validated scenarios of future vegetation with all its climatic shifts.