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M.J. Gaillard, S. Sugita, Florence Mazier, A.-K. Trondman, Anna Brostrom, et al.. Holocene land-cover reconstructions for studies on land cover-climate feedbacks. Climate of the Past, 2010, 6, pp.483-499. 10.5194/cp-6-483-2010 . halshs-00961642

Clim. Past, 6, 483–499, 2010
www.clim-past.net/6/483/2010/
doi:10.5194/cp-6-483-2010

Climate of the Past

Holocene land-cover reconstructions for studies on land cover-climate feedbacks

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Received: 16 February 2010 – Published in Clim. Past Discuss.: 11 March 2010
Revised: 4 June 2010 – Accepted: 22 June 2010 – Published: 26 July 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract. The major objectives of this paper are: (1) to review the pros and cons of the scenarios of past anthropogenic land cover change (ALCC) developed during the last ten years, (2) to discuss issues related to pollen-based reconstruction of the past land-cover and introduce a new method, REVEALS (Regional Estimates of VEgetation Abundance from Large Sites), to infer long-term records of past land-cover from pollen data, (3) to present a new project (LANDCLIM: LAND cover – CLIMate interactions in NW Europe during the Holocene) currently underway, and show preliminary results of REVEALS reconstructions of the regional land-cover in the Czech Republic for five selected time windows of the Holocene, and (4) to discuss the implications and future directions in climate and vegetation/land-cover modeling, and in the assessment of the effects of human-induced changes in land-cover on the regional climate through altered feedbacks. The existing ALCC scenarios show large discrepancies between them, and few cover time periods older than AD 800. When these scenarios are used to assess the impact of human land-use on climate, contrasting results are obtained. It emphasizes the need for methods such as the REVEALS model-based land-cover reconstructions. They might help to fine-tune descriptions of past land-cover and lead to a better understanding of how long-term changes in ALCC might have influenced climate. The REVEALS model is demonstrated to provide better estimates of the regional vegetation/land-cover changes than the traditional use of pollen percentages. This will achieve a robust assessment of land cover at regional- to continental-spatial scale throughout the Holocene. We present maps of REVEALS estimates for the percentage cover of 10 plant functional types (PFTs) at 200 BP and 6000 BP, and of the two open-land PFTs "grassland" and "agricultural land" at five time-windows from 6000 BP to recent time. The LANDCLIM results are expected to provide crucial data to reassess ALCC estimates for a better understanding of the land suface-atmosphere interactions.

1 Introduction

Vegetation (land cover) is an inherent part of the climate system. Natural, primarily climate-driven, vegetation and ecosystem processes interact with human land-use to determine vegetation patterns, stand structure and their development through time (e.g. Vitousek et al., 1997). The resulting land surface properties feed back on climate by modulating exchanges of energy, water vapour and greenhouse gases with the atmosphere. Terrestrial ecosystems may exert biogeochemical (affecting sources and sinks of greenhouse gases [GHG], aerosols, pollutants and other gases) and biophysical (affecting heat and water fluxes, wind direction and magnitude) feedbacks on the atmosphere (e.g. Foley et al., 2003). These feedbacks may be either positive, amplifying changes or variability in climate, or negative, attenuating variability and slowing trends in climate. Carbon cycle feedbacks have received particular attention (Cox et al., 2000; Ruddiman, 2003; Friedlingstein et al., 2003; Meehl et al., 2007); however, biophysical interactions between the land surface and atmosphere can be of comparable importance at the regional scale (Kutzbach et al., 1996; Sellers et al., 1997; Betts, 2000; Cox et al., 2004; Bala et al., 2007). These feedbacks represent a major source of uncertainty in projections of climate under rising greenhouse gas concentrations in the atmosphere (Meehl et al., 2007). Therefore, the incorporation of dynamic vegetation into climate models to account for feedbacks and refine global change projections is a current priority in the global climate modelling community (Friedlingstein et al., 2003; Meehl et al., 2007; van der Linden and Mitchell, 2009). In this context, there is a growing need for spatially explicit descriptions of vegetation/land-cover in the past at continental to global scales for the purpose of improving our mechanistic understanding of processes for incorporation in predictive models, and applying the data-model comparison approach with the purpose to test, evaluate and improve dynamic vegetation and climate models (global and regional). Such descriptions of past land-cover would likewise help us to test theories on climate-ecosystem-human interactions and strengthen the knowledge basis of human-environment interactions (e.g. Anderson et al., 2006; Dearing, 2006; Denman and Brasseur, 2007; Wirtz et al., 2009).

Objective long-term records of the past vegetation/land-cover changes are, however, limited. Palaeoecological data, particularly fossil pollen records, have been used to describe vegetation changes regionally and globally (e.g. Prentice and Jolly, 2000; Williams et al., 2008), but unfortunately they have been of little use for the assessment of human impacts on vegetation and land cover (Anderson et al., 2006; Gaillard et al., 2008). The development of databases of human-induced changes in land cover based on historical records, remotely-sensed images, land census and modelling (Klein Goldewijk, 2001, 2007; Ramankutty and Foley, 1999; Olofsson and Hickler, 2008) has been useful to evaluate the effects of anthropogenic land-cover changes on the past climate (e.g. Brovkin et al., 2006; Olofsson and Hickler, 2008). However, the most used databases to date (i.e. the Klein Goldewijk's database in particular) cover relatively short periods. Recently developed scenarios of anthropogenic land cover change (ALCC) (Pongratz et al., 2008; Kaplan et al., 2009; Lemmen, 2009) include longer time periods. Notably, all these datasets show inconsistent estimates of land cover during key time periods of the past. Therefore, the development of tools to quantify and synthesize records of vegetation/land cover change based on palaeoecological data is essential to evaluate model-based scenarios of ALCC and to improve their reliability.

The major objectives of this paper are: (1) to review the pros and cons of the ALCC scenarios developed by

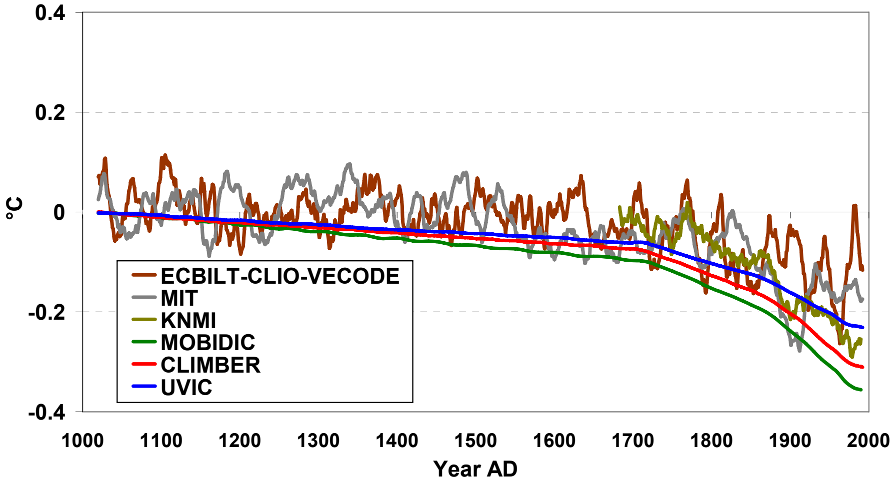


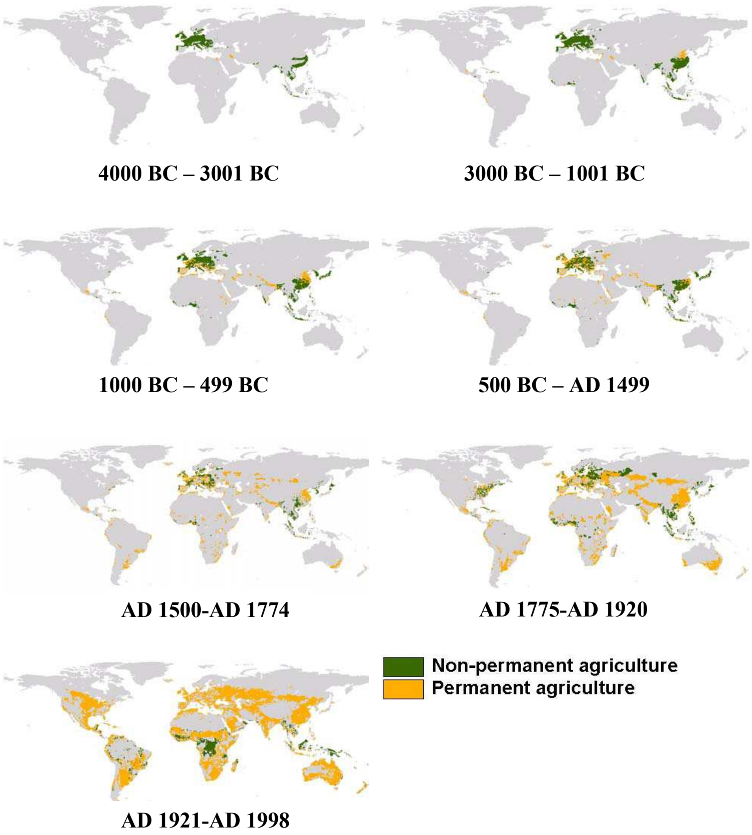
Fig. 1. Decrease in mean global temperature over the Northern Hemisphere due to the biophysical feedback (increased albedo) of an estimated decrease in forest cover between AD 1000 and 2000 as simulated by six different climate models (see details on the climate models in Brovkin et al., 2006). Land-use changes were based on HYDE [History Database of the Global Environment] version 2.0 for the period AD 1700–2000, and on a constant rate of decrease in forest cover between 1000 and 1700 (from Brovkin et al., 2006; modified).

Ramankutty and Foley (1999), Klein Goldewijk (2001, 2007, 2010), Olofsson and Hickler (2008), Pongratz et al. (2008), Kaplan et al. (2009), and Lemmen (2009), (2) to discuss issues related to pollen-based reconstruction of the past vegetation/land-cover and introduce a new method (REVEALS [Regional Estimates of VEgetation Abundance from Large Sites], Sugita, 2007a) to improve the long-term records of vegetation/land-cover, (3) to present a new project (LANDCLIM: LAND cover – CLIMate interactions in NW Europe during the Holocene) currently underway and preliminary results, and (4) to discuss the implications of points 1–3 above, and future directions in the assessment of the effects of human-induced changes in vegetation/land-cover on the regional climate through altered feedbacks. All ages below are given in calendar years AD/BC or BP (present=1950).

2 Databases of past land-cover and land-use changes

As human population and density are generally accepted as the major driver of ALCC, long-term data of past land-cover have generally been inferred from estimates of human population density and cleared land per person. Existing databases of global estimates of past land-use change back to AD 1700 (e.g. Ramankutty and Foley, 1999; Klein Goldewijk, 2001, i.e. the HYDE [History Database of the Global Environment] database version 2.0) and back to AD 800 (Pongratz et al., 2008) were derived by linking recent remote sensed images of contemporary land cover and land census data to past human population censuses. Brovkin et al. (2006) used the HYDE database to reconstruct land-use feedbacks on climate over the past 1000 years; but due to the lack of palaeodata synthesis of past land-cover, the rate of decrease in forest cover between AD 1000 and 1700 was assumed constant. In that study, the outputs from six different climate models showed a cooling of 0.1 °C to 0.4 °C over the Northern Hemisphere due to the biophysical feedback (increased albedo) of an estimated decrease in forest cover between AD 1000 and 2000 (Fig. 1).

Olofsson and Hickler (2008) were the first to present an estimate of transient changes in carbon emissions caused by land-use on Holocene time scales. They used archaeological maps of the spread of different societal forms ("states and empires" and "agricultural groups"; Lewthwaite and Sherrat, 1980), the HYDE reconstruction (version 2.0) for the last 300 years, global changes in population (primarily based on McEvedy and Jones, 1978), and an estimate of land suitability to derive land transformation for farmland and pastures by humans at different time windows (Fig. 2). Permanent agriculture was assumed to be associated with the development of states and empires, leading to 90% deforestation of the suitable land, and non-permanent (slash-and-burn) agriculture was implemented also in suitable areas dominated by agricultural groups. Their reconstruction (Fig. 2) shows two main centres of early agriculture in the Far East and in Europe-Near East, characterized mainly by non-permanent agriculture from 4000 BC until 1000 BC. In Europe, permanent agriculture is represented mainly in France, Spain, and Italy during the time window 1000 BC–AD 499. From AD 500, permanent agriculture spread northwards and eastwards. The major change is seen between the time windows AD 1775–1920 and AD 1921–1998, most non-permanent agriculture outside the tropics being replaced by permanent agriculture. It is striking that permanent agriculture in Europe does not differ much between the time windows AD 1500–



4000 BC – 3001 BC

3000 BC – 1001 BC

1000 BC – 499 BC

500 BC – AD 1499

AD 1500-AD 1774

AD 1775-AD 1920

AD 1921-AD 1998

Fig. 2. Reconstructions of the spatial extent of permanent and non-permanent agriculture for seven time slices of the Holocene (modified from Olofsson and Hickler, 2008). The reconstructions are based on archaeological maps of the spread of different societal forms, HYDE [History Database of the Global Environment] version 2.0 for the last 300 years, global changes in population, and an estimate of land suitability (see text for details).

1774 and AD 1775–AD 1920. The 19th century is known in several regions of Europe as the time of most intensive land-use with a maximum of landscape openness, while the 20^{th} century was characterized by a reforestation after abandonment and/ or through plantation, e.g. in southern Scandinavia, southern Norway, northern Italy, Central France, the Pyerenees, Central Spain, Portugal (Krzywinski et al., 2009; Gaillard et al., 2009). The latter landscape transformation is not evidenced in the map for the time window AD 1921–AD 1998; instead it shows an increase in the areas of permanent agriculture compared to the former period. This is probably mainly due to the version (2.0) of HYDE used in the reconstruction. In the most recent version of HYDE (3.1) the landscape transformation during the 20th century (compared to the 19th century) is more visible.

Pongratz et al. (2008) estimated the extent of cropland and pasture since AD 800. Their reconstruction is based on published maps of agricultural areas for the last three centuries with a number of corrections. For earlier times, a country-based method was developed that uses population data as a proxy for agricultural activity. The resulting reconstruction of agricultural areas is combined with a map of potential vegetation to estimate the resulting historical changes in land cover. One of the strengths of the study is that the uncertainties associated with the approach, in particular owing to technological progress in agriculture and human population estimates, were quantified. These uncertainties vary between regions of the globe (for more details, see Pongratz et al., 2008). This reconstruction shows that by AD 800, 2.8 million km^2 of natural vegetation had been transformed to agricultural land, which is about 3% of the area potentially covered by vegetation on the globe. This transformation resulted from the development of almost equal proportions of cropland and pasture. Around AD 1700, the agricultural area had increased to 7.7 million km^2; 3.0 million km^2 of forest had been cleared (85% for cropland, 15% for pasture) and 4.7 million km^2 of grassland and shrubland were under human use (30% for the cultivation of crop). Thus, between AD 800 and AD 1700, natural vegetation under agricultural use had increased by ca. 5 million km^2. Within the next 300 years, the total agricultural area increased to 48.4 million km^2 (mainly pastureland), i.e. a ca. 5.5 times

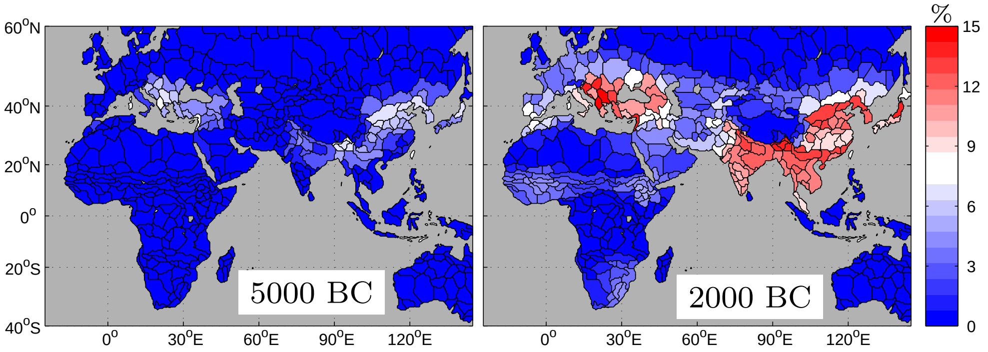


Fig. 3. Fractional crop cover at 5000 BC (left) and 2000 BC (right) simulated by the Global Land use and Technological Evolution Simulator (GLUES, Lemmen, 2009).

larger area than at AD 1700. This reconstruction shows that global land cover change was small between AD 800 and AD 1700 compared to industrial times, but relatively large compared to previous millennia. Moreover, during the preindustrial time period of the last millennium, the reconstruction shows clear between-region differences in histories of agriculture.

Recently, Kaplan et al. (2009) created a high resolution, annually resolved time series of anthropogenic deforestation in Europe over the past three millennia. Their model was based on estimates of human population for the period 1000 BC to AD 1850 and the suitability of land for cultivation and grazing (pasture) ("standard scenario"). Assumptions include that high quality agricultural land was cleared first, and that marginal land was cleared next. A second alternative scenario was produced by taking into account technological developments ("technology scenario"). The latter produces major differences in land cover in south western, south eastern and eastern Europe where landscape openness becomes significantly lower than in the "standard scenario", whereas it is higher in western Europe.

Lemmen (2009) developed an independent estimate of human population density, technological change and agricultural activity during the period 9500–2000 BC based on dynamical hindcasts of socio-economic development (GLUES [Global Land Use and technological Evolution Simulator], Wirtz and Lemmen, 2003). The population density estimate was combined with per capita crop intensity from HYDE (version 3.1) to infer areal demand for cropping at an annual resolution in 685 world regions. At 2000 BC, the simulation exhibits a continuous belt of higher crop fraction (compared to earlier times) across Eurasia, and intensive cropping around the Black Sea and throughout South and East Asia (Lemmen, 2009) (Fig. 3). The transition to agriculture in these areas required that up to 13% of the local vegetation cover was replaced by crop land at 2000 BC, especially in the heavily populated areas of East and South Asia, in south eastern Europe and the Levant. A comparison to the simulated crop-land fractional area at 5000 BC shows an intensification of agriculture at 2000 BC in the ancient centres of agriculture (Near East, Anatolia, Greece, China, Japan), and the development of extensive agriculture visible in the spread of crops spanning the Eurasian continent at subtropical and temperate latitudes, and the emergence of agriculture in Africa (Fig. 3). At 5000 BC, GLUES simulated a crop fraction of up to 7% in the early agricultural centres (Levante, Southeast Europe, China, Japan). The distribution of agriculture around 2000 BC reconstructed by Lemmen (2009) agrees with the estimates of Olofsson and Hickler (2008) in Japan, China, West Africa and Europe. Major differences in Olofson and Hickler's dataset are (1) the discontinuity between the East Asian and Western Eurasian agriculture (Figs. 2, 5), especially through the Indian subcontinent, and (2) the distinction between permanent and non-permanent agriculture, which was not attempted in GLUES.

The differences between the maps of Kaplan et al. (2009) and the HYDE database at AD 1800 are striking. The model results of Kaplan et al. (2009) provide estimates of deforestation in Europe around AD 1800 that compare well with historical accounts (Krzywinski et al., 2009; Gaillard et al., 2009), whereas this is not the case for the HYDE database. Even though the maps by Olofsson and Hickler (2008) (Figs. 2, 5) are difficult to compare with those of Kaplan et al. (2009) because of the difference in scale (global and continental, respectively), type (permanent/non-permanent agriculture and cultivation/pasture, respectively) and unit (areas under permanent/non permanent agriculture or forested fraction of grid cell, respectively) of the reconstructed landscape openness, the maps of Kaplan et al. (2009) show generally more open landscapes between 1000 BC and AD 1850 than the maps of Olofsson and Hickler (2008). This is primarily because Olofsson and Hickler take only agriculture into account, while Kapplan et al. include grazing land. Kaplan et al. (2009) also show more extensive European deforestation at AD 800 than the HYDE and Pongratz et al. (2008)'s databases (Fig. 4), and the reconstruction by Olofsson and Hickler (2008) for the time window 500 BC–AD 1499 (Fig. 2). Similarly, Kaplan et al. (2009)'s map

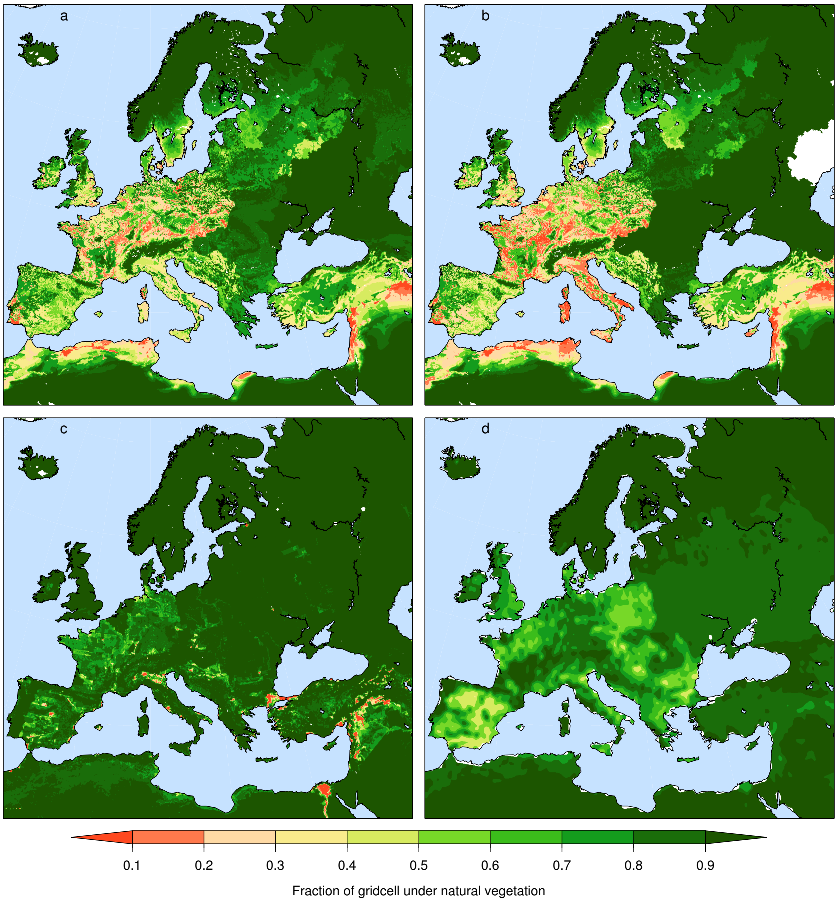


Fig. 4. Anthropogenic land use in Europe and surrounding areas at AD 800 simulated by four different modelling approaches: **(a)**, the Kaplan et al. (2009) standard scenario; **(b)**, the Kaplan et al. (2009) technology scenario; **(c)**, the HYDE [History Database of the Global Environment] database version 3.1 (Klein Goldewijk et al., 2010); **(d)**, the Pongratz et al. (2008) maximum scenario.

for AD 1 exhibits much larger deforested areas than HYDE (over the entire globe) and the map by Olofsson and Hickler (2008) for the time window 500 BC–AD 1499 (in particular in Central and Eastern South America, central Africa, the Near East and India) (Fig. 5). This implies that previous attempts to quantify anthropogenic perturbation of the Holocene carbon cycle based on the HYDE and Olofsson and Hickler's databases may have underestimated early human impact on the climate system. Lemmen (2009) compared his simulated crop fraction estimate with the HYDE estimate and found only local agreement (e.g. along the Yellow River in northern China, in the greater Lebanon area in the Near East and on the Italian peninsula), while most of the GLUES-simulated cropland area is not apparent in the HYDE database; the discrepancy was attributed to missing local historical data in HYDE. Krumhardt et al. (2010) compared the human population density from GLUES extrapolated to 1000 BC with the estimate by Kaplan et al. (2009) based on McEvedy and Jones (1978) and found a very good match for many countries and subcontinental regions.

3 Pollen-based reconstruction of past vegetation and land cover

Fossil pollen has been extensively used to estimate past vegetation in sub-continental to global scales. However, most studies have focused on forested vegetation. For instance, Williams et al. (2008) used a modern-analogue approach to estimate the past Leaf Area Index (LAI) in Northern America. They tested their approach using a modern training dataset and showed that it performed satisfactorily for a majority of the high number of records used. In northern Eurasia, Tarasov et al. (2007) developed a method to infer the percentage cover of different tree categories (such as needle-leaved, deciduous, or evergreen trees) from pollen data. Their results showed that pollen-inferred tree-cover is often too high for most tree categories particularly north of 60° latitude. The observed discrepancies illustrate the palynologists' well-known problems related to 1) pollen-vegetation relationships when pollen data is expressed in percentages, 2) the definition of the spatial scale of vegetation represented by pollen, and 3) the differences in pollen productivity between plant

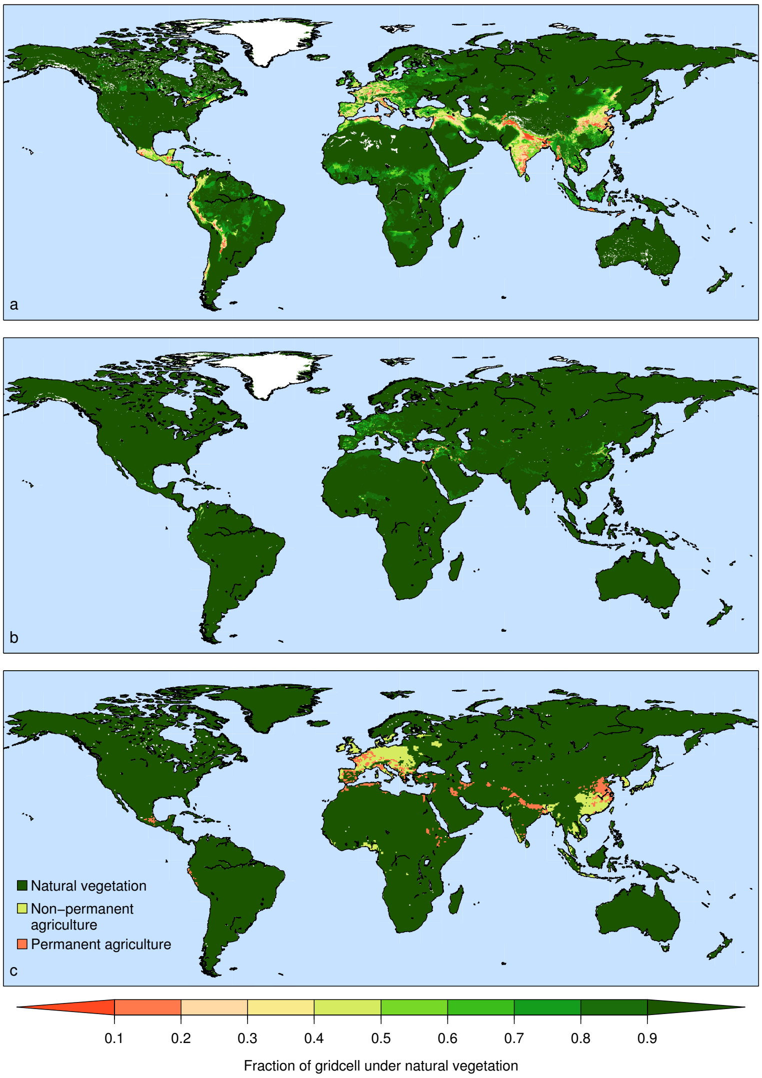


Fig. 5. Global anthropogenic land use at AD 1 simulated by three different approaches: **(a)**, Kaplan et al. (2009); **(b)**, HYDE [History Database of the Global Environment] version 3.1 (Klein Goldewijk et al., 2010); and **(c)**, Olofsson and Hickler (2008). Note that the colour scale is relevant for maps (a) and (b). Map (c) has its own colour legend.

taxa (e.g. Prentice, 1985, 1988; Sugita et al., 1999; Gaillard, 2007; Gaillard et al., 2008). The pollen-vegetation relationship in percentages is not linear because of, in particular, percentage calculations, the effects of long-distance pollen from regional sources, and the characteristics of the regional vegetation and the deposition basins (e.g. Sugita et al., 1999; Hellman et al., 2009). Therefore, for similar deposition basins – in terms of type (bog, lake, etc.) and size –0% and 100% of a taxon in the vegetation cover will not necessarily correspond to 0% and 100 % pollen of that same taxon, respectively. Further, e.g. 20% pollen of a given taxon may represent different percentage covers of that taxon in the vegetation (e.g. 40, 50, 60 or 80%) depending on the characteristics of the regional vegetation and the deposition basin.

The non-linear nature of the pollen-vegetation relationship has made it difficult to quantify past land-cover changes using fossil pollen (e.g. Andersen, 1970; Prentice, 1985, 1988; Sugita et al., 1999; Gaillard, 2007; Gaillard et al., 2008). However, earlier developments in the theory of pollen analysis (Andersen, 1970; Prentice, 1985; Sugita, 1994) have contributed to the recent development of a new framework of vegetation/land-cover reconstruction, the Landscape Reconstruction Algorithm (LRA) (Sugita, 2007a, b). LRA solves the problems related with the non-linear nature of pollen-vegetation relationships, and corrects for biases due to differences in pollen dispersal and deposition properties between plant species, landscape characteristics, species composition of vegetation, and site size and type (bog or lake). The LRA consists of two separate models, REVEALS and

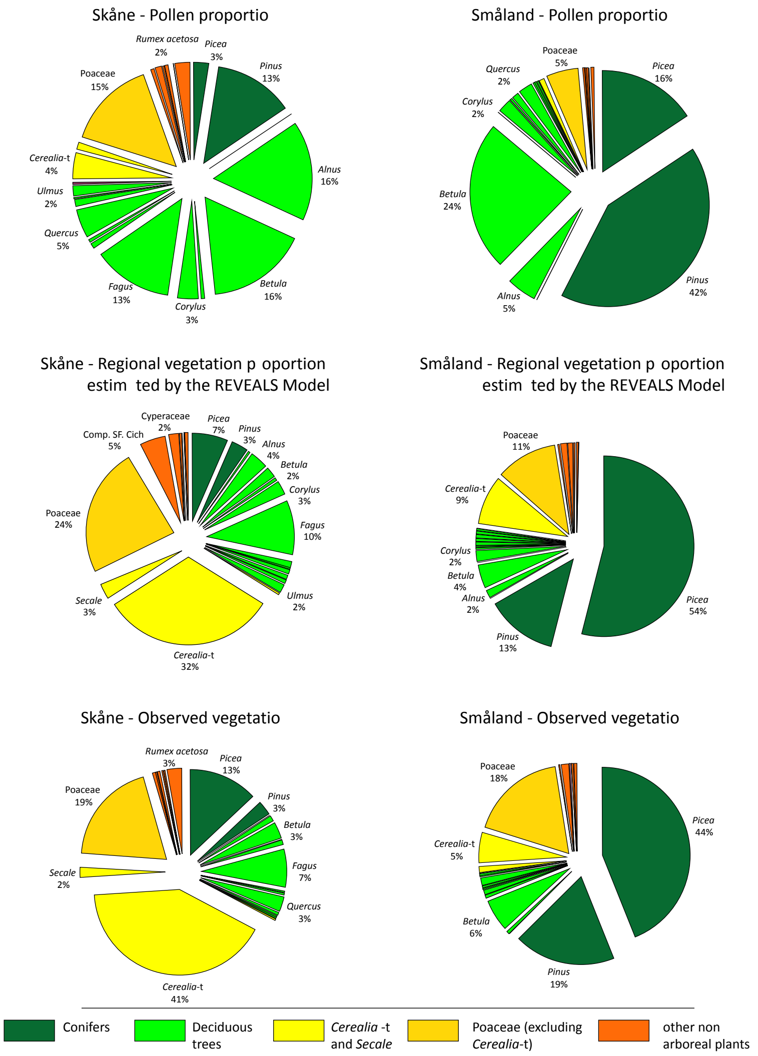


Fig. 6. Validation of the REVEALS model in southern Sweden, provinces of Skåne (left) and Småland (right): comparison of pollen percentages, REVEALS estimates, and actual vegetation for 26 taxa. See Fig. 8 for the locations of Skåne and Småland. Only taxa represented by $\geq$ 2% are named. REVEALS was run with the pollen productivity estimates from southern Sweden (Broström et al., 2004). Note the underrepresentation in pollen percentages of cereals (yellow), Poaceae (grasses; orange) and other non-arboreal taxa (herbs and shrubs; red), and the overrepresentation of deciduous trees (light green), *Betula* (birch) and *Alnus* (alder) in particular, compared to the share of these taxa in the actual vegetation and in REVEALS estimates. *Pinus* (pine) is dominant among conifers (dark green) in the pollen assemblage, while *Picea* (spruce) is dominant in the vegetation and REVEALS estimates. Other deciduous trees: *Corylus* (hazel), *Fagus* (beech), *Quercus* (oak), *Ulmus* (elm). Cereals: Cerealia-t (cereals, rye excluded), *Secale* (rye); other non-arboreal taxa (herbs): Compositae Sub-Family Cichorioideae (lettuce, dandelions and others), Cyperaceae (sedges), *Rumex acetosa*-t (sorrels, in particuler common sorrel and sheep's sorrel). The taxa with values <2% in pollen assemblages, actual vegetation and REVEALS estimates are: Deciduous trees – *Acer* (maple), *Tilia* (linden), *Carpinus* (hornbeam), *Fraxinus* (ash), *Salix* (willows); Other non arboreal taxa – *Juniperus* (juniper), *Calluna* (heather), *Filipendula* (meadowsweets), *Potentilla* (cinquefoils), *Ranunculus acris* type (buttercups), *Rubiaceae* (bedstraws), and *Plantago lanceolata* (ribwort). For details, see Hellman et al. (2008a, b).

LOVE (LOcal Vegetation Estimates), allowing vegetation abundance to be inferred from pollen percentages at the regional (10^4–10^5 km^2 area) and local ($\leq$100 km^2 area) spatial scale, respectively. Extensive simulations support the theoretical premise of the LRA (Sugita, 1994, 2007a, b). The effectiveness of REVEALS and has been empirically tested and shown to be satisfactory in southern Sweden (Hellman et al., 2008a, b) (Fig. 6), central Europe (Soepboer et al., 2010), and the upper Great Lakes region of the US (Sugita et al., 2010). Moreover, Hellman et al. (2008a) showed that REVEALS provided better estimates of the land-cover composition in southern Sweden than those obtained in earlier studies using the "correction factors" of Andersen (1970) and Bradshaw (1981) to account for biases

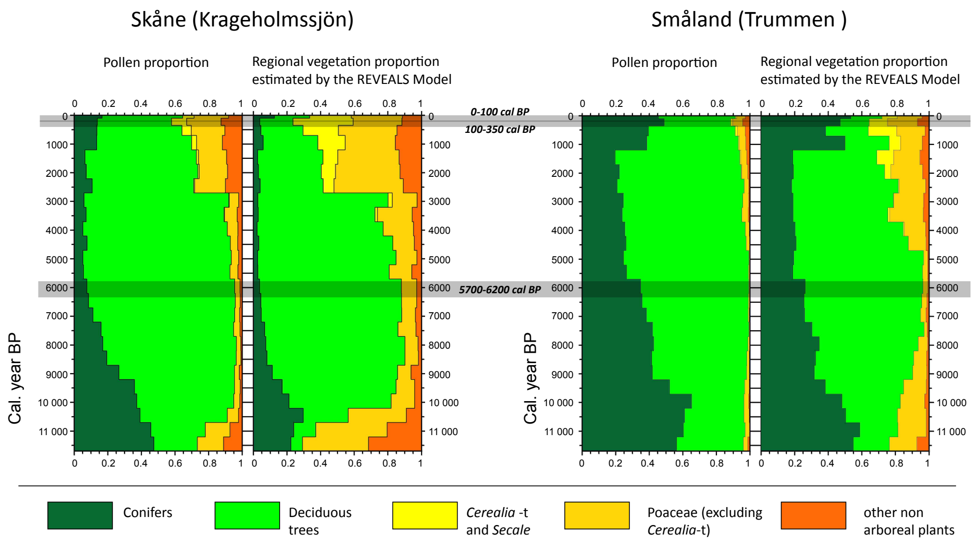


Fig. 7. REVEALS reconstructions of Holocene vegetation changes (right in each panel) in southern Sweden based on the pollen records (left in each panel) from Kragehomssjön (province of Skåne, left) and Lake Trummen (province of Småland, right) (from Sugita et al., 2008, modified). See Fig. 8 for the locations of Skåne and Småland. The selected three major time-windows studied in the LANDCLIM project are indicated. REVEALS was run with 24 pollen taxa with the pollen productivity estimates from southern Sweden (Broström et al., 2004). The taxa included in the groups "conifers", "deciduous trees", "Cerealia-t" (cereals, rye excluded) and "other non-arboreal plants" (herbs and shrubs) are the same as in Fig. 6. *Secale*=rye; Poaceae=grasses.

due to between-species/taxa differences in pollen productivity (Björse et al., 1996; Lindbladh et al., 2000), or applying the self-organized mapping method (neural networks) combined with the "correction factors" (Holmqvist and Bradshaw, 2008).

The first REVEALS-based reconstructions of Holocene vegetation in southern Sweden indicate that changes in human impact on vegetation/land-cover over the last 6000 years, as well as landscape openness during the Early Holocene (11 500–10 000 cal. yrs BP), were much more profound than changes in pollen percentages alone would suggest (Sugita et al., 2008) (Fig. 7). The proportion of unforested land through the Holocene is strongly underestimated by percentages of Non Arboreal Pollen (NAP, i.e. pollen from herbaceous plants). For instance, at the regional spatial scale, the REVEALS estimates of openness represented by non-arboreal taxa during the last 3000 years reached 60–80% in the province of Skåne, and 25–40% in the province of Småland (compared to 30–40% and 3–10% of NAP, respectively). The REVEALS reconstruction of the regional vegetation of the Swiss Plateau for the past 2000 years also showed that the area of open land is underestimated by NAP percentages (Soepboer et al., 2010).

4 The LANDCLIM Initiative and Preliminary Results

The LANDCLIM (LAND cover – CLIMate interactions in NW Europe during the Holocene) project and research network has the overall aim to quantify human-induced changes in regional vegetation/land-cover in northwestern and western Europe north of the Alps (Fig. 8) during the Holocene with the purpose to evaluate and further refine a dynamic vegetation model and a regional climate model, and to assess the possible effects on the climate development of two historical processes (compared with a baseline of present-day land cover), i.e. climate-driven changes in vegetation and human-induced changes in land cover, e.g. via the influence of forested versus non-forested land cover on shortwave albedo, energy and water fluxes.

Accounting for land-surface changes may be particularly important for regional climate modelling, as the biophysical feedbacks operate at this scale and may be missed or underestimated at the relatively coarse resolution of Global Circulation Models (GCMs). Dynamic Global Vegetation Models (DVMs) (Cramer et al., 2001; Prentice et al., 2007) have been coupled to GCMs to quantify vegetation – mainly carbon cycle – feedbacks on global climate (e.g. Cox et al., 2000; Friedlingstein et al., 2003). Current DVMs are necessarily highly generalized and tend to represent vegetation structure and functioning in abstract and rather simplified ways (e.g. Sitch et al., 2003). For application at the regional scale, and to fully account for biophysical feedbacks on climate, a more detailed configuration of vegetation and processes governing its dynamics is needed (Smith et al., 2001; Wramneby et al., 2009). The LPJ (Lund Potsdam Jena) – GUESS (General Ecosystem Simulator) model (LPJ-GUESS, Smith

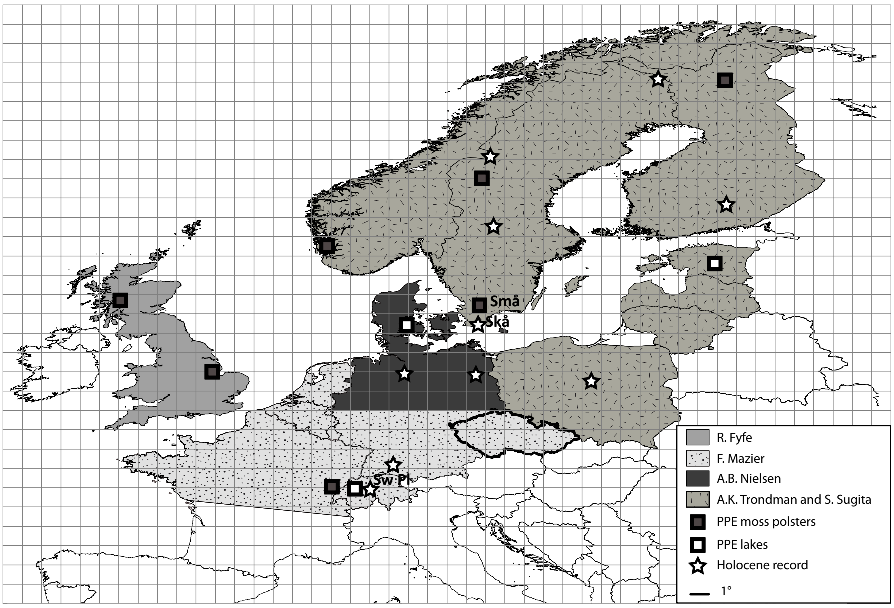


Fig. 8. Study area of the LANDCLIM project. It is devided between four principal investigators. The regions where pollen productivities were estimated from modern pollen data (in moss polsters or surface lake sediments) and related vegetation data are indicated. REVEALS reconstructions performed within the LANDCLIM project are presented in Figs. 10 and 11 for the Czech Republic (emphasized by a thick land boarder). REVEALS reconstructions of vegetation changes over the entire Holocene will be performed for 10 target sites (indicated by stars on the map); such reconstructions are presented in Fig. 7 for the provinces of Skåne (Skå) and Småland (Små).

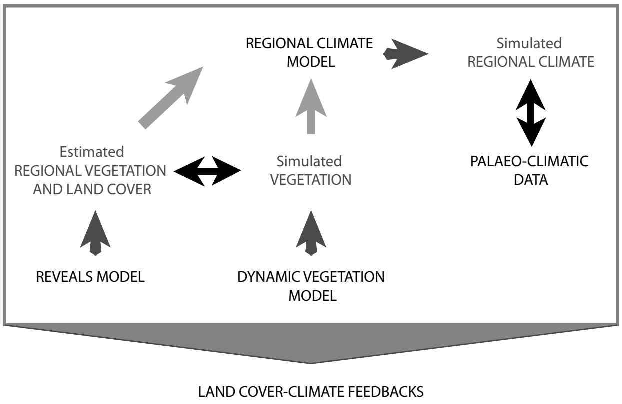


Fig. 9. Model-data comparison scheme for the LANDCLIM project. The simple arrows represent model inputs or outputs. The double arrows represent the model-data comparison steps. REVEALS model (Sugita 2007a); dynamic vegetation model= LPJ-GUESS (Smith et al., 2001); regional climate model=RCA3 (Kjellström et al., 2005). For details, see text.

et al., 2001) is a dynamic, process-based vegetation model optimized for application across a regional grid that simulates vegetation dynamics based on climate data input. It represents landscape and stand-scale heterogeneity and, by resolving horizontal and vertical vegetation structure at these scales, more adequately accounts for the biophysical properties that influence regional climate variability.

The Rossby Centre Regional Atmospheric model version 3 (RCA3) is capable of realistically simulating the European climate of the last couple of decades (Kjellström et al., 2005; Samuelsson et al., 2010). RCA3 and its predecessors RCA1 and RCA2 have been extensively used for this kind of downscaling experiments for today's climate and future climate change scenarios (Rummukainen et al., 1998, 2001; Jones et al., 2004; Räisänen et al., 2003, 2004; Kjellström et al., 2010a). LPJ-GUESS has been interactively coupled to RCA3 (Wramneby et al., 2009) and is being used to study the feedbacks of climate-driven vegetation changes on climate, via changes in albedo, roughness, hydrological cycling and surface energy fluxes. Preliminary results suggest that changes in treelines, phenology of conifer versus broadleaved trees, and LAI may modify the future climate development, particularly in areas close to treelines and in semi-arid areas of Europe (Wramneby et al., 2009).

The aims of the LANDCLIM project will be achieved by applying a model-data comparison scheme using the LPJ-GUESS, RCA3, and REVEALS models, as well as new syntheses of palaeoclimatic data (Fig. 9). The REVEALS estimates of the past cover of plant functional types (PFTs) at a spatial resolution of $1^\circ \times 1^\circ$ will be compared with the outputs of LPJ-GUESS (10 PFTs), and used as an alternative to the LPJ-GUESS-simulated vegetation (3 PFTs) to run RCA3 for the recent past (0–100 cal BP) and selected time windows of the Holocene with contrasting human-induced land-cover at 100–350 BP, 350–700 BP (Black Death), 2700–3200 BP

Table 1. PFTs used in the LANDCLIM project (see text for more explanations). The ten PFTs in the left column and the three land-surface types in the right column are used in the dynamic vegetation model LPJ-GUESS and regional climate model RCA3, respectively. The PFTs are a simplification of the PFTs described in Wolf et al. (2008). The corresponding 24 plant taxa for which REVEALS reconstructions are performed in the project are indicated in the middle column. These plant taxa have specific pollen-morphological types; when the latter corresponds to a botanical taxon, it has the same name; if not, it is indicated by the extension "–t".

PFT	PFT definition	Plant taxa/Pollen-morphological types	Land surface
TBE1	Shade-tolerant evergreen trees	*Picea*	Evergreen tree canopy
TBE2	Shade-tolerant evergreen trees	*Abies*	
IBE	Shade-intolerant evergreen trees	*Pinus*	
TSE	Tall shrub evergreen trees	*Juniperus*	
IBS	Shade-intolerant summergreen trees	*Alnus, Betula, Corylus, Fraxinus, Quercus*	Summergreen tree canopy
TBS	Shade-tolerant summergreen trees	*Carpinus, Fagus, Tilia, Ulmus*	
TSD	Tall shrub summergreen trees	*Salix*	
LSE	Low evergreen shrub	*Calluna*	Open land
GL	Grassland – all herbs	Cyperaceae, *Filipendula*	
		Plantago lanceolata	
		Plantago montana	
		Plantago media	
		Poaceae	
		Rumex p.p. (mainly *R. acetosa R. acetosella*) */Rumex acetosa*-t	
AL	Agricultural land – cereals	Cereals (Secale excluded)/Cerealia-t, *Secale*	

(Late Bronze Age), and 5700–6200 BP (Early Neolithic). The outputs of the RCA3 model will then be compared to the palaeoclimatic data. The REVEALS model estimates the percentage cover of species or taxa that are grouped into the PFTs used in the LPJGuess and RCA3 models as shown in Table 1. Moreover, time trajectories of land-cover changes for the entire Holocene will be generated in ten selected target areas of the project's study region (Fig. 8) to be compared with long-term simulated vegetation dynamics from LPJ-GUESS.

REVEALS requires raw pollen counts, site radius, pollen productivity estimates (PPEs), and fall speed of pollen (FS) to estimate vegetation cover in percentages. PPEs and FS are now available for 34 taxa in the study area of the LANDCLIM project (Broström et al., 2008) (Fig. 8). The study area is divided between four principle investigators (Fig. 8). A protocol was established in order to standardize the strategy and methods applied for the preparation of the pollen data and the REVEALS runs (LANDCLIM website). The pollen records are selected from pollen databases, i.e. the European Pollen Database (EPD) (Fyfe et al., 2007), the PALYnological CZech database (PALYCZ) (Kuneš et al., 2009) and the ALpine PALynological DAtaBAse (ALPADABA), or they are obtained directly from the authors. A Spearman rank order correlation test was applied on the REVEALS estimates obtained using the pollen records from PALYCZ in order to test the effect on the REVEALS estimates of (1) basin type (lakes or bogs), (2) number of pollen taxa, (3) PPEs dataset, and (4) number of dates per record used to establish the chronology (≥3 or ≥5) (Mazier et al., 2010). The results showed that the REVEALS estimates are robust in terms of ranking of the PFTs' abundance whatever alternatives were used to run the model. Therefore, the first REVEALS estimates produced use pollen records from both lakes and bogs, chronologies established with ≥ 3 dates, 24 pollen taxa (entomophilous taxa excluded) and, for each pollen taxon, the mean of all PPEs available for that taxon in the study area (Trondman et al., 2010).

Examples of preliminary results for the Czech Republic are presented in three series of maps (Figs. 10 and 11). As expected, there are significant vegetation changes between 6000 BP and 200 BP in particular for *Abies* (TBE 2; ca. 5–10 times larger cover at 200 BP), summer-green trees (IBS and TBS; ca. 5 times larger cover at 6000 BP), grasslands (GL; ca. 5–10 times larger cover at 200 BP in many areas) and agricultural land (AL; 4 to 9 times larger cover at 200 BP in many areas) (Fig. 10). The maps of herbaceous PFTs (AL and GL) show significant changes in the degree of human-induced vegetation between the selected time windows, with the largest change between 2700–3200 BP and 350–700 BP, and a decrease in cover of GL between 100–350 BP and 0–100 BP (Fig. 11), which agrees with the known historical development in many parts of Europe due to forest plantation or abandonment of grazing areas.

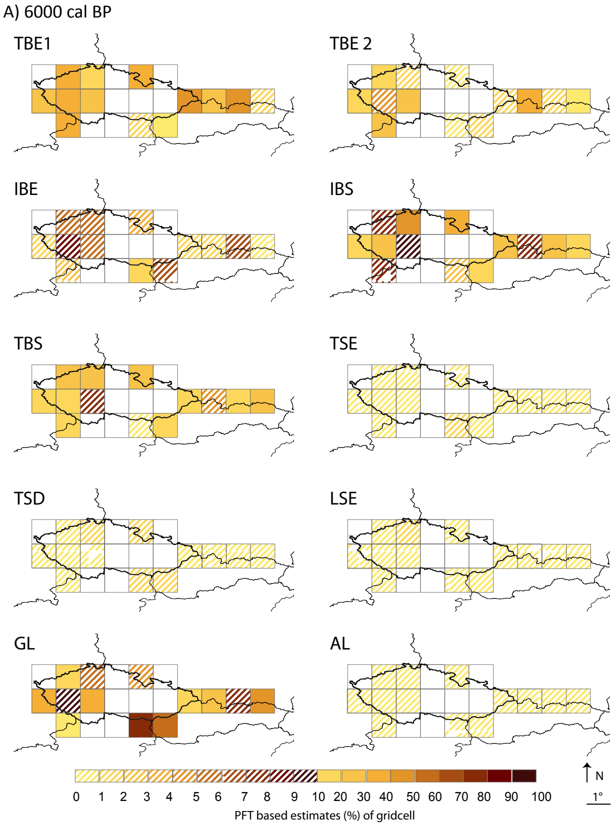


Fig. 10a. REVEALS estimates of ten plant functional estimates (PFTs) for the Czech Republic at 6000 BP **(A)** and 200 BP **(B)** using the PALYCZ pollen database (Kuneš et al., 2009) and following the LANDCLIM project's protocol. The definition of the PFTs are found in Table 1. In this visualization of the results, the zero values (no occurrence of a PFT) are not distinguised from values >0% up to 1%. Note the large difference in the open-land PFTs between 6000 and 200 BP, with up to 80% grassland (GL, grasses and herbs) and up to 9% agricultural land (AL, cereals) at 200 BP, compared to maximum 50% grassland (except in the SE) and ≤1% agricultural land at 6000 BP. A thorough discussion of these results will be published elsewhere (Mazier et al., 2010).

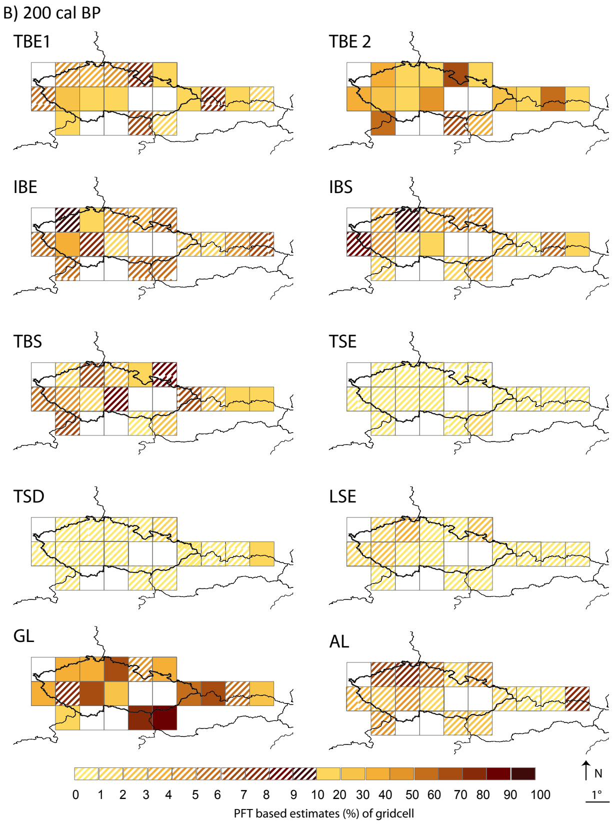


Fig. 10b. Continued.

5 Implications and future directions

Palaeoenvironmental reconstructions are critical to provide predictive models of climate and environmental changes with input data, and for model evaluation purposes. Climate models are becoming increasingly complex; they are composed of several modules, of which one shall represent a dynamic land biosphere. The latter is in turn composed of a large number of "sub-models" (e.g. stomata, phenology, albedo, dynamic land cover, carbon flow, soil models). All the processes involved in these "sub-models" are influenced by natural and human-induced vegetation changes. Thus, the dynamic land-cover model should also account for anthropogenic land-cover change. It should be noted here that biophysical feedbacks from land-cover change were not accounted for by the main IPCC climate models (IPCC Fourth Assessment Report, 2007).

The REVEALS model provides better estimates of the regional vegetation/land-cover changes, and in particular for open, herb-dominated (NAP) areas, than the traditional use of pollen percentages and earlier attempts at correcting or calibrating pollen data (e.g. Sugita 2007a; Hellman et al., 2008a, b). REVEALS thus allows a more robust assessment of human-induced land cover at regional- to continental-spatial scale throughout the Holocene. The LANDCLIM project and NordForsk network are designed to provide databases on the regional changes in vegetation/land-cover in north-western Europe that should prove to be useful to fine-tune LPJ-GUESS and evaluate RCA3.

LPJ-GUESS has been previously shown to be capable of reproducing patterns and time series of vegetation response to climate (e.g. Smith et al., 2001; Hickler et al., 2004; Miller et al., 2008). Seppä et al. (2009) compared assemblages of *Pinus* (pine), *Picea* (spruce) and *Betula* (birch) inferred from Holocene pollen accumulation rates (PARs) from two southern Finnish lakes with predictions of the biomass of these taxa from LPJ-GUESS; a disagreement between the modelled and pollen-based vegetation for *Pinus* after 2000 years

BP was associated to a period of greater anthropogenic influence in the area surrounding the study sites. REVEALS reconstructions will make it possible to further evaluate this assumption and the performance of LPJ-GUESS itself.

RCA3 was used earlier in palaeoclimatological contexts to simulate the north European climate during more than 600 out of the last 1000 years (Moberg et al., 2006), for the Last Glacial Maximum (Strandberg et al., 2010), and for a cold stadial during Marine Isotope Stage 3 (Kjellström et al., 2010b). Simulations of Holocene climate for periods older than 1000 BP and fine-tuning the coupled land-cover properties in RCA3 as planned in the LANDCLIM project might contribute to further improve the robustness of the model. Moreover, RCA3 is currently applied in other parts of the world (Africa, the Arctic, South and North America), and the results show that the model is capable of simulating the climate in a range of different climate zones throughout the world. This implies that the approach of the LANDCLIM project could, in the future, be applied to regions other than Europe.

REVEALS-based land-cover reconstructions will be informative for evaluating other hypotheses that involve land cover-climate feedbacks. Many studies have focused on the effects of land-use change on global-scale fluxes of carbon from terrestrial ecosystems (e.g. DeFries et al., 1999; McGuire et al., 2001; Houghton, 2003; Campos et al., 2005). However, these estimates do not extend beyond AD 1700, and estimated ALCC was mostly extracted from the digital HYDE database version 2.0. The studies to date that do consider the effects of ALCC on the terrestrial carbon budget on longer time scales, including those by Claussen et al. (2005) and Olofsson and Hickler (2008), agree in the suggestion that the magnitude of past changes in terrestrial carbon balance associated with human land-use are far too small to account for a major dampening (or enhancement) of global climate variations (e.g. the Ruddiman's hypothesis; Ruddiman, 2003, 2005). On the other hand, a recent data-base synthesis of ALCC in the Western Hemisphere following European colonization and the subsequent collapse of indigenous populations suggested that the magnitude of the carbon uptake from regrowing forests in the 16th and 17th centuries could have been partly responsible for the slightly lower atmospheric CO_2 concentrations observed during the Little Ice Age cold period (Nevle and Bird, 2008). These contrasting results emphasize the need for empirical data of past land-cover such as the REVEALS model-based reconstructions, which might help to fine-tune descriptions of past land-cover and lead to a better understanding of how long-term changes in ALCC might have influenced climate. The LANDCLIM results are expected to provide crucial data to reassess ALCC estimates (e.g. Olofsson and Hickler, 2008; Pongratz et al., 2008; Kaplan et al., 2009; Lemmen, 2009) and a better understanding of the land surface-atmosphere interactions at the regional spatial scale. Although biophysical exchanges operate at the local to regional scale, the feedbacks can have consequences elsewhere, through remote adjustments in temperatures, cloudiness and rainfall by means of circulation changes (Dekker et al., 2007). Comparison between studies of land cover-climate feedbacks at both regional and global spatial scales will increase our understanding of climate change.

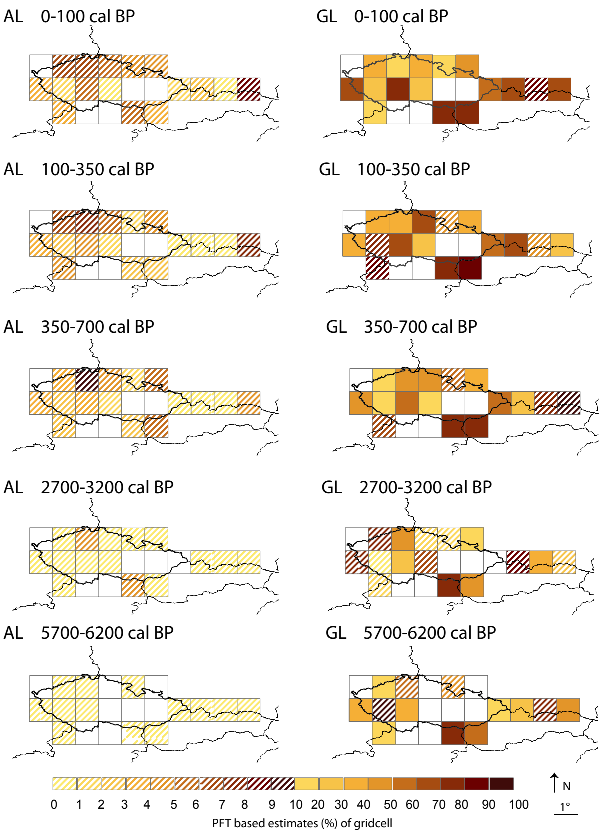


Fig. 11. REVEALS estimates of the two open-land plant functional estimates (PFTs), AL (agricultural land=cereals) and GL (grassland=grasses and other herbs) for the Czech Republic at five time slices using the PALYCZ pollen database (Kuneš et al., 2009) and following the LANDCLIM project's protocol. In this visualization of the results, the zero values (no occurrence of a PFT) are not distinguised from values >0% up to 1%. Note the distinct changes and the maintenance of spatial differences through time, e.g. the high representation of grassland in the South-East from 6000 BP, and the higher representation of agricultural land in the North from 3000 BP. A thorough discussion of these results will be published elsewhere (Mazier et al., 2010).

Pollen-based reconstruction of vegetation and land-cover changes needs further collaboration for compilation of reliable land-cover databases. The REVEALS model is a useful tool for this task, in addition to the currently available methods (e.g. Williams et al., 2008). REVEALS estimates of the regional vegetation/land cover are currently available for the five LANDCLIM time windows for Sweden, Finland, Denmark, Britain, Poland, the Czech Republic, Switzerland

and Northern Germany; REVEALS estimates are underway for Norway, Estonia, Southern Germany, France, Belgium, and the Netherlands. Pollen productivity estimates (PPEs) of open-land plants and major tree taxa, important parameters necessary to run REVEALS, are still limited outside NW Europe (Broström et al., 2008), North America (Sugita et al., 2010) and South Africa (Duffin and Bunting, 2008); however, new studies are currently underway in southern Europe, Japan, China, and Africa (Cameroon), and more is to come within the Focus 4 (Past Human-Climate-Ecosystem Interactions; PHAROS) of the International Geosphere-Biosphere Programme - Past Global Changes (IGBP PAGES). Therefore, we expect that more objective descriptions of past land-cover will be available for several regions of the world in the near future.

Acknowledgements. The LANDCLIM (LAND cover – CLIMate interactions in NW Europe during the Holocene) project and research network are sponsored by the Swedish [VR] and Nordic [NordForsk] Research Councils, respectively, and coordinated by Marie-José Gaillard. The two initiatives are a contribution to the IGBP-PAGES-Focus 4 PHAROS programme (http://www.pages-igbp.org/science/focus4) on human impact on environmental changes in the past. The foundation for major parts of this paper is the IGBP-PAGES Focus 4 Meeting held in July 2008 at the Royal Society, London, funded by PAGES and the Royal Society. Marie-José Gaillard thanks Frank Oldfield and John Dearing for their interest in the work performed within the NordForsk POLLANDCAL and LANDCLIM networks, and their ever-lasting support through the years. The authors are also grateful to all members of the LANDCLIM network (beside all co-authors) who contribute pollen data and the information needed to apply REVEALS. Other funding sources include the Faculty of Natural Sciences of Linnaeus University (Kalmar-Växjö, Sweden) for Marie-José Gaillard and Anna-Kari Trondman, the Estonian Science Foundation (MTT3) for Shinya Sugita, the German National Science Foundation (DFG priority program Interdynamik) for Carsten Lemmen, and the VR Linnaeus grant "Lund Centre for studies of Carbon Cycle and Climate Interaction, LUCCI" (grant number: VR 349-2007-8705) for Florence Mazier. The authors are thankful to both reviewers, Pavel Tarasov and Scott Mooney, and to the editor Thorsten Kiefer for useful comments and corrections. Scott Mooney in particuler has made many suggestions that significantly improved the language of the manuscript.

Edited by: T. Kiefer

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