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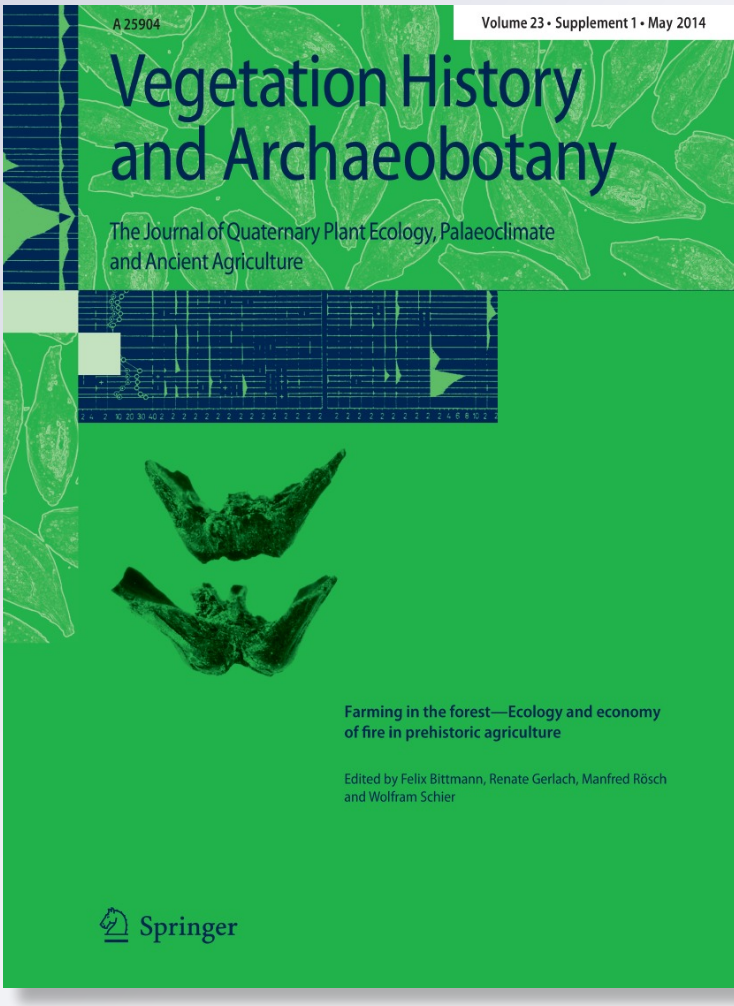
Vegetation History and Archaeobotany
The Journal of Quaternary Plant Ecology, Palaeoclimate and Ancient Agriculture - Official Organ of the International Work Group for Palaeoethnobotany

ISSN 0939-6314
Volume 23
Supplement 1

Veget Hist Archaeobot (2014)
23:109-119
DOI 10.1007/s00334-013-0418-y



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ORIGINAL ARTICLE

Reconstruction of Holocene vegetation, tree cover dynamics and human disturbances in central European Russia, using pollen and satellite data sets

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Received: 1 March 2013 / Accepted: 24 September 2013 / Published online: 8 October 2013

Abstract This paper presents an assessment of Holocene tree cover densities and forest disturbance in European Russia using the best-modern-analogue (BMA) technique of quantitative reconstruction and an innovative approach, which combines modern pollen datasets with remotely sensed data from moderate-resolution imaging spectroradiometer satellite images. The test of the accuracy of the applied method using a database of 450 sets of surface pollen assemblages shows that it can reproduce present day characteristics of woody cover in Europe correctly ($R^2 = 0.57$, standard error = 10.8 %), and it is sufficient for reconstruction of major changes of woodland vegetation in the past. Application of the BMA technique to fossil pollen data from two key regions in the central part of European Russia demonstrates that changes in regional woody cover are useful for the reconstruction of prehistoric human disturbance.

Keywords Palaeoenvironment reconstruction · Tree cover · Forest disturbance · Pollen data · MODIS satellite images · Holocene

Communicated by F. Bittmann.

Electronic supplementary material The online version of this article (doi:10.1007/s00334-013-0418-y) contains supplementary material, which is available to authorized users.

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Introduction

Pollen-based reconstruction of vegetation dynamics is a very effective tool for investigation of human activity in the past. Early assessments of human impact on vegetation were based on qualitative determination and indicator species analyses (Behre 1981; Vuorela 1986; Zernitskaya and Mikhailov 2009), as well as using relatively simple statistical models that related percentages of arboreal and non-arboreal pollen (NAP) to landscape openness (Frenzel et al. 1992; Rösch 1992; Broström et al. 1998; Sugita et al. 1999). More sophisticated modelling approaches took into consideration the influence of background pollen (Caseldine and Fyfe 2006), along with the relevant pollen source area and productivity (Broström et al. 2005, 2008). Reconstruction of historical land cover using pollen data was further advanced with the introduction of sophisticated models, such as the Landscape Reconstruction Algorithm or Regional Estimates of Vegetation Abundance from Large Sites (REVEALS) (Sugita 2007), which were subsequently applied to reconstruct regional vegetation during the Holocene in different regions of Europe (Gaillard et al. 2008; Nielsen et al. 2012).

An innovative technique to quantify changes in cover during the late Pleistocene and Holocene was recently applied to pollen spectra from North America (Williams 2003; Williams and Jackson 2003) and northern Asia (Tarasov et al. 2007). This method combined modern and fossil pollen records and satellite-based tree cover data (Hansen et al. 2003) with the best-modern-analogue (BMA) approach (Overpeck et al. 1985; Guiot 1990), which is based on searching for the closest analogues of fossil spectra among the modern datasets. These studies demonstrated that the new technique can be very effective for reconstructing variation in density of tree cover, and could provide new frameworks for quantitative assessment of human disturbance of vegetation.

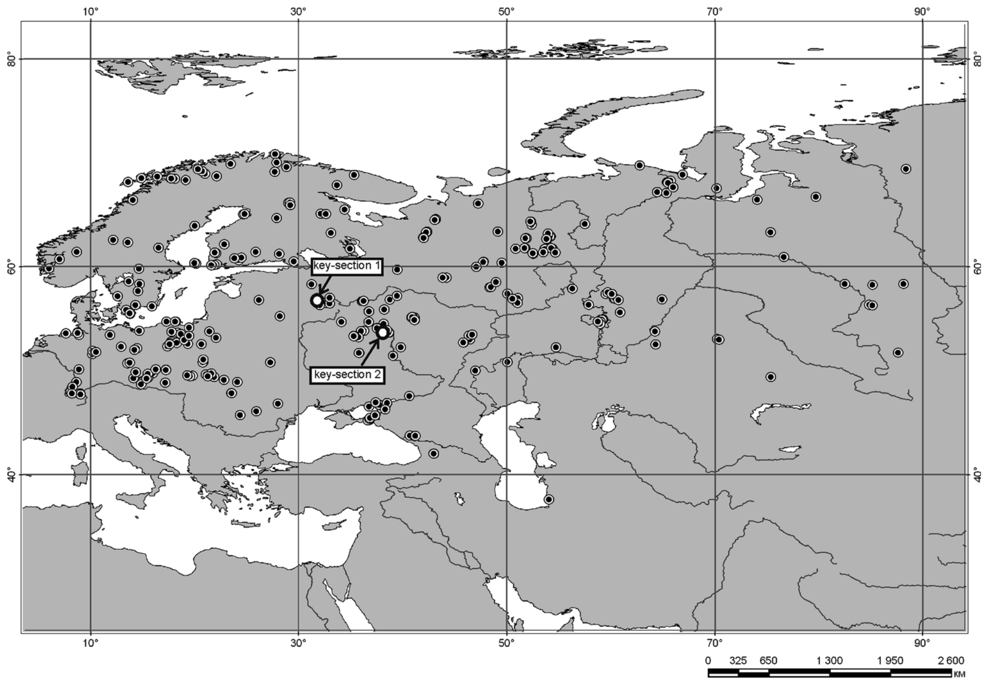

Fig. 1 Map of north-western Eurasia with locations of the reference pollen data set of 450 surface spectra used in the woodland cover reconstruction. The *white circles* indicate the position of the key regions for reconstructions

Our study is on human-environment interactions in European Russia during the Holocene. The main objectives of the study were (1) to create a reference dataset consisting of surface pollen spectra and associated satellite-based estimates of tree cover, (2) to assess the accuracy of regional tree cover reconstructions using the BMA approach applied to the reference modern dataset, and (3) to apply the method for reconstruction of tree cover disturbance in two key regions in the central part of European Russia. We also incorporated previously published pollen and micro-charcoal data into the analysis, along with reconstructions of vegetation during the Holocene.

Study area

We selected two key regions located in the central part of the East European plain to describe human-environment interactions during the Holocene (Fig. 1). The regions are characterized by various vegetations of mixed coniferous-broadleaved forest and forest-steppe, climate, geomorphological structure and soil. The regions furthermore differ in their degree of human influence, which have allowed us to reconstruct and analyze human impact on plant cover under contrasting natural conditions.

The first region, the Central Forest State Natural Biosphere Reserve (CFSNBR), is situated about 360 km west of Moscow (the Tver' region) in the southern part of the Valdai upland. This territory was located along the margin of the Weichselian ice sheet and is a slightly hilly area, with elevations of 220–250 m a.s.l. The highest moraine ridge in the south part of the CFSNBR (up to 280 m a.s.l.) is also the main watershed divide in the East European plain between the Caspian and the Baltic basins.

The climate of the area is moderate continental with relatively mild winters and warm summers. According to meteorological observations conducted in the CFSNBR the mean July temperature is 17 °C, January is −10 °C, and the mean annual temperature is 3.8 °C. Annual precipitation does not exceed 700 mm per year.

Vegetation of the CFSNBR is composed of primary forest with minimal human disturbance. *Picea abies* (spruce) forests dominate in vegetation cover (47 %), followed by *Betula pubescens* and *B. verrucosa* (birch) and *Populus tremula* (aspen) woods (40 %), which form due to windfalls and forest fires. River valleys are occupied by *Alnus glutinosa* (alder) communities (1–2 %), while mires and swamp pine woods cover 6 and 10 %, respectively.

Conditions during at least the last 600 years were unfavourable for agriculture due to intense paludification over much of the territory. As a result, the role of arable land in land use has been minimal and the possibility of arable or pastoral farming strongly dependent on regional climatic and soil moisture fluctuations. Local farmers during the past c. 100 years were forced to abandon their land due to a climate-induced rise in the water table.

The pollen records used for reconstruction of human impact on vegetation were derived from an 8 m deep borehole located in the central part of a relatively large (617 ha) mire—Staroselsky Moch (N56.28548, E32.02772). The peat bog occupies the series of depressions in the upper part of the watershed area of the Mezha (river Daugava basin) and

Tudovka (upper river Volga system). The lowermost radiocarbon age of the peat deposits is 9,730 ± 100 cal. B.P. Pollen and plant macrofossil analysis and radiocarbon dating of this borehole have been presented in detail in Novenko et al. (2009c).

The second region, the so-called Kulikovo Battlefield area, is located in the upper river Don basin (Tula region) and is the place of the famous battle where, in A.D. 1380, the Russians defeated the Tartar-Mongol forces. It is situated on the northern slopes of the Mid-Russian upland (Fig. 1). The landscape consists of small, evenly undulating plateaus at 210–234 m a.s.l., separated by elongated narrow valleys.

The present-day climate there is temperate and moderately continental, with a mean annual temperature around +3.8 °C and mean January and July temperatures of −10.6 and +18.4 °C, respectively. The precipitation is 534 mm per year (http://www.meteo.ru).

The vegetation of the region combines woodland and herbaceous plant communities. Small areas of broad-leaved woods still exist in the upper Don basin and its tributaries; however, the natural plant cover has been greatly changed by human impact since the early stages of settlement of the area. According to available archaeological records, the area includes Neolithic and Bronze Age sites and more than 250 medieval settlements (Gonianyi et al. 2007). The present-day landscape is almost entirely treeless, with natural woodland and herbaceous communities replaced by agricultural land that is either in use or abandoned.

The landscape dynamics and land use changes in the forest-steppe zone of the upper river Don basin in the mid- and late Holocene have been intensively investigated (Folomeev et al. 1990; Gonianyi et al. 2007; Novenko et al. 2009a, 2012). In our paper we discuss pollen and micro-charcoal evidence, backed by radiocarbon dates, resulting from the study of the Podkosmovo mire within the Kulikovo Battlefield area.

The Podkosmovo mire (53.67027°N, 38.59055°E) is located in the floodplain of the river Nepryadva, the right tributary of the river Don, and covers a surface area of 1.2 ha. The fen is fed by ground water seeping from the base of the valley slope as well as by lateral floodwater. Although the thickness of peat deposits is 1.2 m, peat accumulation began about 5,042 ± 80 cal. B.P.

Data and methods

Fossil pollen, micro-charcoal and radiocarbon data

Field work, coring and sediment description were carried out in the CFSNBR during several summer field campaigns in 2004–2006 and in the Kulikovo Battlefield area in 2009. The peat cores were obtained using a Russian corer 50 cm long with a 5 cm inner diameter chamber. The sediments of Staroselsky Moch bog were subsampled for pollen analysis at 10 cm intervals, and the Podkosmovo mires samples at 3–5 cm.

Samples were prepared for pollen analysis using the pollen extraction procedure developed by Grichuk (1940). The treatment included separation by heavy liquid (cadmium iodide) with a density of 2.2 g/cm^3. Calculation of relative pollen frequency is based upon the total terrestrial pollen sum, arboreal pollen (AP) plus (NAP). Aquatic plants, Cyperaceae and spores were excluded. A minimum of 500 pollen grains per sample was counted (AP+NAP). Pollen diagrams were compiled using Tilia and Tilia Graph (Grimm 1990). For calculating pollen and micro charcoal concentrations, *Lycopodium* tablets were added to each sample during the pollen preparation process (Stockmarr 1971). Concentration of microscopic charcoal was assessed using a Zeiss Axiostar microscope at 400× magnification using Clark's point-count method (Clark 1982; Finsinger

Table 1 Radiocarbon dates of the studied sediment cores

Lab. no.	Depth (cm)	Dated material	^{14}C age (B.P.)	Cal. age, 1σ-range (cal. B.P.)
Staroselsky moch peat bog				
IG RAN 3279	100–105	Peat	1,620 ± 130	1,505 (1,382–1,628)
IG RAN 3280	170–175	Peat	1,830 ± 70	1,852 (1,840–1,865)
IG RAN 3281	300–305	Peat	3,860 ± 170	4,261 (4,073–4,449)
IG RAN 3282	400–405	Peat	5,010 ± 130	5,772 (5,644–5,900)
IG RAN 3286	500–505	Peat	7,190 ± 120	8,048 (7,932–8,164)
IG RAN 3330	550–557	Gyttja	8,700 ± 180	9,729 (9,528–9,929)
Podkosmovo peat bog				
IG RAN 4070	20–23	Peat	607 ± 95	598 (480–656)
IG RAN 4071	60–64	Peat	2,345 ± 70	2,407 (2,357–2,457)
IG RAN 4072	80–82	Peat	4,405 ± 80	5,042 (4,924–5,158)

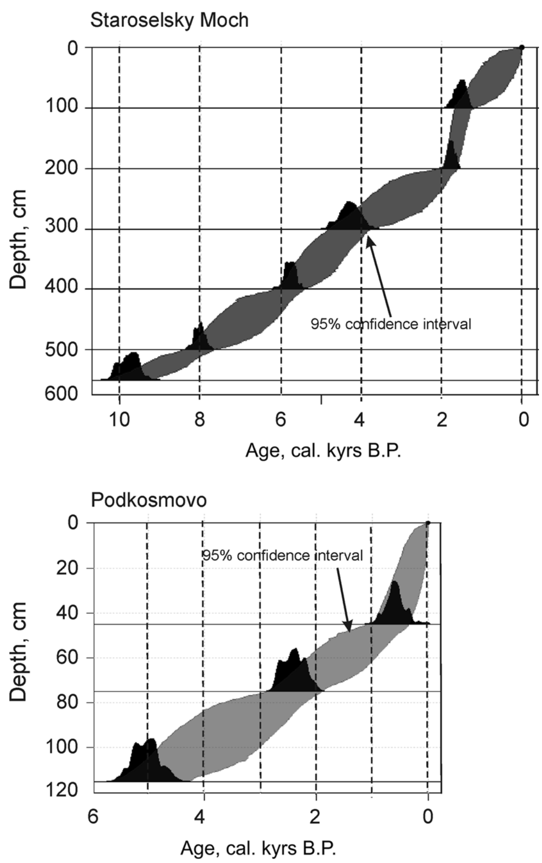

Fig. 2 Age-depth models of the studied sediment cores

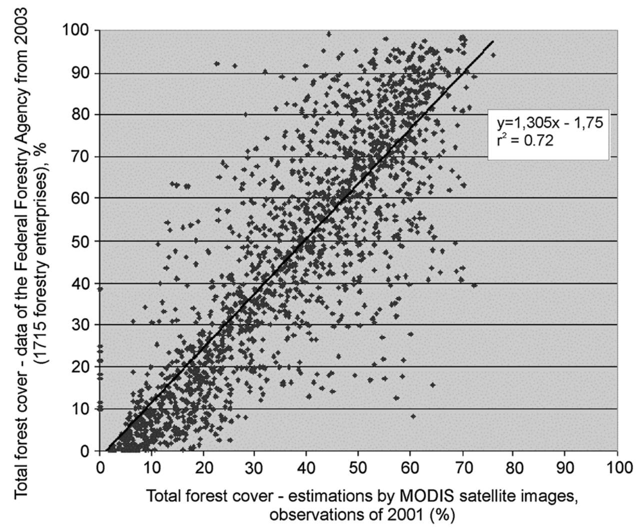

Fig. 3 *Scatterplots* comparing the MODIS-based observations (2001) of total tree cover from 2001 with data of the Federal Forestry Agency from 2003 (after Ershov 2007)

et al. 2008), and at least 200 items (the sum of charcoal particles and *Lycopodium* spores) were counted (Finsinger and Tinner 2005).

Radiocarbon dating was performed in the Radiocarbon Laboratory of the Institute of Geography of the Russian Academy of Science (Table 1). The ^{14}C dates were calibrated using Calib 6.0 and the calibration dataset Intcal04 (Reimer et al. 2004). Calculations have been done at 1σ level. The age-depth models of the cores were made in Bchron software (Fig. 2; Parnell et al. 2008).

Modern pollen datasets

The palaeoenvironmental reconstructions which are based on comparison between modern and fossil pollen spectra (analogue technique) require a high-quality extensive database of surface pollen assemblages. In this study we used 450 pollen datasets originating from a wide variety of landscapes in Europe, including European Russia and Siberia (Fig. 1). Modern surface samples were derived from the European Pollen Database (EPD) (http://www.europeanpollendatabase.net) and from a new Russian pollen data base (http://pollendata.org), which was developed by the authors of this paper. Our own surface samples were collected in the period 2000–2011. Additionally we used top samples of pollen sequences from the EPD which were published from 1998 onwards.

A taxon list of the reference data set comprises 45 selected pollen types, the values of which exceed 0.5 % in the pollen assemblages, the universal threshold suggested by Prentice et al. (1996), who defined it in order to avoid possible problems related to long-distant pollen transport, re-deposition or incorrect identification of rare pollen types (ESM 1).

Remote-sensing data

We used the VCF (Vegetation Continuous Fields) estimates of modern tree cover (Hansen et al. 2003), which detail the proportion of each 500 × 500 m pixel that is covered by trees, herbs, and bare ground, for the entire world. The VCF is derived from observations of the moderate-resolution imaging spectroradiometer (MODIS) carried onboard NASA's Terra satellite (http://glcf.umiacs.umd.edu/data/vcf). In our studies we used the VCF product collection 4, produced from MODIS observations in 2005.

Nowadays MODIS satellite images are used for land cover mapping and determination of forest disturbance by human-induced fires and clear cutting (Bartalev et al. 2004, 2011). Comparison of MODIS-based estimates of tree cover in European Russia with the data of the Federal Forestry Agency (Ershov 2007) from areas of 1,715 forestry enterprises (Fig. 3) showed that the remote-sensing data provided a reasonable assessment of forest coverage ($R^2 = 0.70$), although it tended to underestimate coverage in areas with very dense forest (more than 70 %). A wide incorporation of MODIS-based estimates of tree cover in the modern forestry industry (Bartalev et al. 2004, 2011; Ershov 2007) caused us to use MODIS data as the analogue for our reconstructions.

In our study, the proportion of forested land within a 20 km radius of each surface pollen assemblage collection site from the reference dataset was calculated by averaging the per-pixel MODIS estimates of tree cover. The 20 km radius roughly corresponds to the pollen source area for small lakes and mires often studied by pollen analysts (Bradshaw and Webb 1985). Even for large lakes, about 60 % of the pollen comes from within 25 km of the shore (Hellman et al. 2008). Pollen and satellite-based reconstructions of woody cover in northern Asia (Tarasov et al. 2007) showed a high correlation between observed and predicted values over a 21 × 21 km window. In the present work we used this experience as the first attempt to determine the characteristic radius for reconstruction of human impact on vegetation.

BMA (best modern analogue) method

The total woody cover in the key region during the Holocene was reconstructed in our study using the BMA technique. Details of the BMA approach, first developed by Overpeck et al. (1985) and extended by Guiot (1990), are presented in many publications devoted to palaeoenvironmental reconstructions (Nakagawa et al. 2002; Williams and Jackson 2003; Tarasov et al. 2007).

The principle of this technique is as follows: (1) to compare the fossil pollen assemblage with modern pollen assemblages using squared-chord distances (SCD) (Overpeck et al. 1985) as the index of dissimilarity between pollen spectra: two spectra were judged analogous if their SCDs were less than a threshold T. (2) to select for each fossil assemblage N (3–10) of the closest modern pollen assemblages (or the best modern analogues). The environmental characteristics (temperature, precipitation, proportion of woodlands, etc.) of these selected best analogues are then averaged to provide the necessary estimates of the fossil assemblage. We experimented with T (0.1–0.6 at 0.1 intervals) and N (5–10), but found that these parameters only slightly influenced the generally reasonable correlation coefficients between MODIS observations and BMA reconstructions. However, lowering the threshold from 0.4 to 0.1 increased the number of non-analogue situations. In the present study we set the threshold to 0.4 and kept the eight best modern analogues. BMA calculations were done with Polygon 1.5 (http://dendro.naruto-u.ac.jp/nakagawa/).

Analogue selection was geographically constrained (Williams and Shuman 2008). We used surface pollen spectra only from places in which the modern vegetation and environmental conditions could be considered theoretically as potentially analogous for Holocene

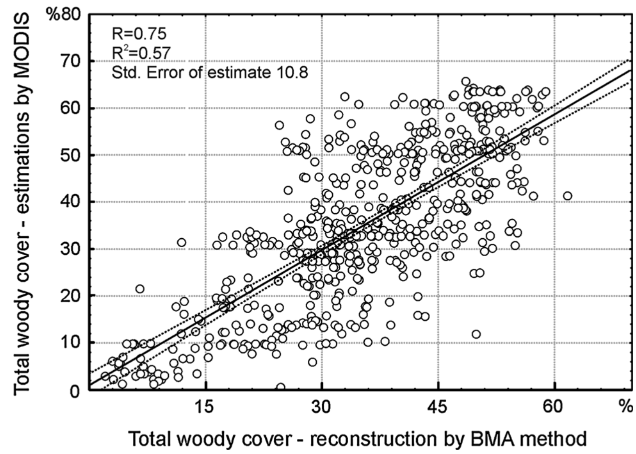

Fig. 4 *Scatterplots* comparing the original MODIS-based observations of total tree cover with the analogue-based percent woody cover estimates for the modern pollen sites

palaeoenvironments in the forest zone of the East European plain. Therefore we restricted the area of calibration datasets to the northern and eastern part of Europe and West Siberia.

To test the accuracy of regional woody cover reconstructions using the BMA approach, a leave-one-out cross-validation has been applied to the reference modern dataset (Ter Braak 1995). One modern pollen spectrum was sequentially removed from the total modern data set. The total woody cover in a radius of 20 km around the site for the removed pollen spectrum was calculated on the basis of the remaining modern data set by the BMA method, and the results were compared with the known value of woody cover around this site.

Results and discussions

Test of the method with modern data

The leave-one-out cross-validation has shown a relatively good correlation of pollen-based modern woody cover reconstructions with original MODIS measurements (Fig. 4; $R^2 = 0.57$ and standard error [SE] 10.8 %), that is basically sufficient for reconstruction of major changes in woody vegetation.

A comparison between present-day percent tree cover generated using the original MODIS-based observations and the pollen-based reconstructions for the modern pollen sites shows a reasonably good correlation between the data sets (Fig. 5). The significantly higher than observed woody cover estimates appeared in the forest-steppe and forest-tundra regions and may be due to long-distance transport of AP. The second source of uncertainty is the time gap between when the MODIS data were collected and when

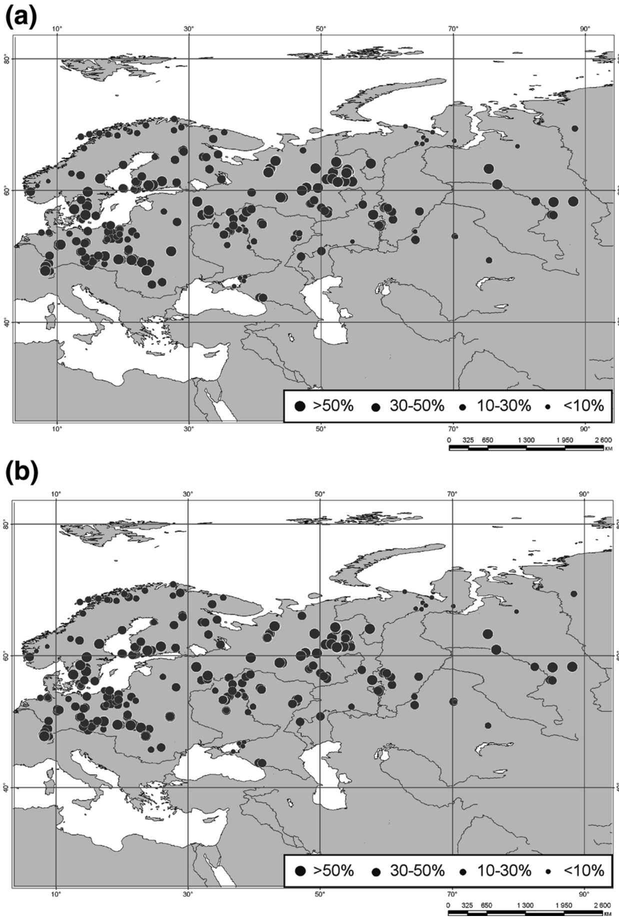

Fig. 5 Maps of present-day percent tree cover generated using the original MODIS-based observations and the pollen-based reconstructions for the modern pollen sites: **a** MODIS-based observation; **b** pollen-based reconstructions

the pollen assemblages were produced by vegetation. For instance, if the pollen data were collected long before or after the satellite imagery, then changes in the landscape during that time could lead to false estimations of tree cover at the time of pollen collection. However, in the present study the time gap between the MODIS observation and pollen sampling does not exceed 5–7 years, during which time large changes are not to be expected, considering the modern state of land use in Europe.

Reconstructions of vegetation and human impact in the mixed coniferous-broadleaved forest zone (the Central Forest Biosphere Reserve)

Pollen sequences of the Staroselky Moch peat bog in the Central Forest Biosphere Reserve allow us to describe the vegetation history and land use changes in the south part of the Valdai upland in the Late-glacial and Holocene (Novenko et al. 2009c).

Environmental dynamics of the Late-glacial were reconstructed using data from the lowermost layers in the profile (Fig. 6). Vegetation cover of the reserve area was formed by *Picea* and *Pinus-Betula* woodlands and herbaceous communities (PAZ 1 and 2, depth 550–650 cm, Fig. 6). Spread of open periglacial landscapes is indicated by abundance of Poaceae, Chenopodiaceae and *Artemisia* among the NAP. The reconstruction of total woody cover around the Staroselky Moch mire demonstrates that the amount of woodland in the vegetation varied from 20 to 40 %, suggesting rather open vegetation like modern forest-steppe (Fig. 6; Bartalev et al. 2011).

In the initial phase of the Holocene (PAZ 3, depth 500–550 cm, 9,730–8,700 cal. B.P.), birch woods dominated the plant cover of the reserve area. Numerous birch macrofossils identified in the Staroselsky Moch profile belong to *Betula pubescens* (Novenko et al. 2009c). The coverage of woody vegetation was relatively low (20–30 %). However the proportion of trees could be underestimated since the early Holocene vegetation has no close analogues in modern plant cover (Gonzales et al. 2009) and use of the BMA approach presents some difficulties.

The first part of the Atlantic period (PAZ 4, depth 470–500 cm, 8,048 ± 50 cal. B.P.) is distinguished by increasing broad-leaved tree pollen values. Apart from broad-leaved trees (*Quercus, Tilia, Ulmus*), *Picea* penetrated into the area, forming coniferous and broadleaved woodland. Increase of *Alnus* pollen in samples indicates an occurrence of communities of alder woods (PAZ 5, depth 375–470 cm). Estimation of past woody cover suggests a quick expansion of trees and shrubs after 8,000 cal. B.P. During the period 5,770–4,420 cal. B.P. (PAZ 6, depth 250–375 cm) the proportion of broad-leaved trees in woods of the CFSNBR was relatively high and the role of spruce as the main woodland tree increased. The share of woodland vegetation in the area maintained relatively high (more than 60 %).

Although archaeological finds within the CFSNBR are unknown, evidence of probable human impact on woodland ecosystems in the vicinity of Staroselsky Moch mire are found in pollen spectra from 4,000 cal. B.P. onwards. The pollen assemblages demonstrate the sharp increase of *Betula* pollen values, noticeable falls of *Picea* and *Alnus*, and the presence of Cerealia and *Centaurea cyanus.* The short-term reduction of total woody cover density (up to 40 %) can be interpreted to indicate disturbance of vegetation by humans.

The next phase of human activity is detected by pollen data at about 1,800–1,500 cal. B.P. (PAZ 7, depth 60–250 cm). In the famous chronicles of tenth to twelfth centuries, the “Povest’ vremennych let” (Karimov and Nosova 1999), the modern area of the Central Forest Reserve was described as a vast and pathless Okovsky

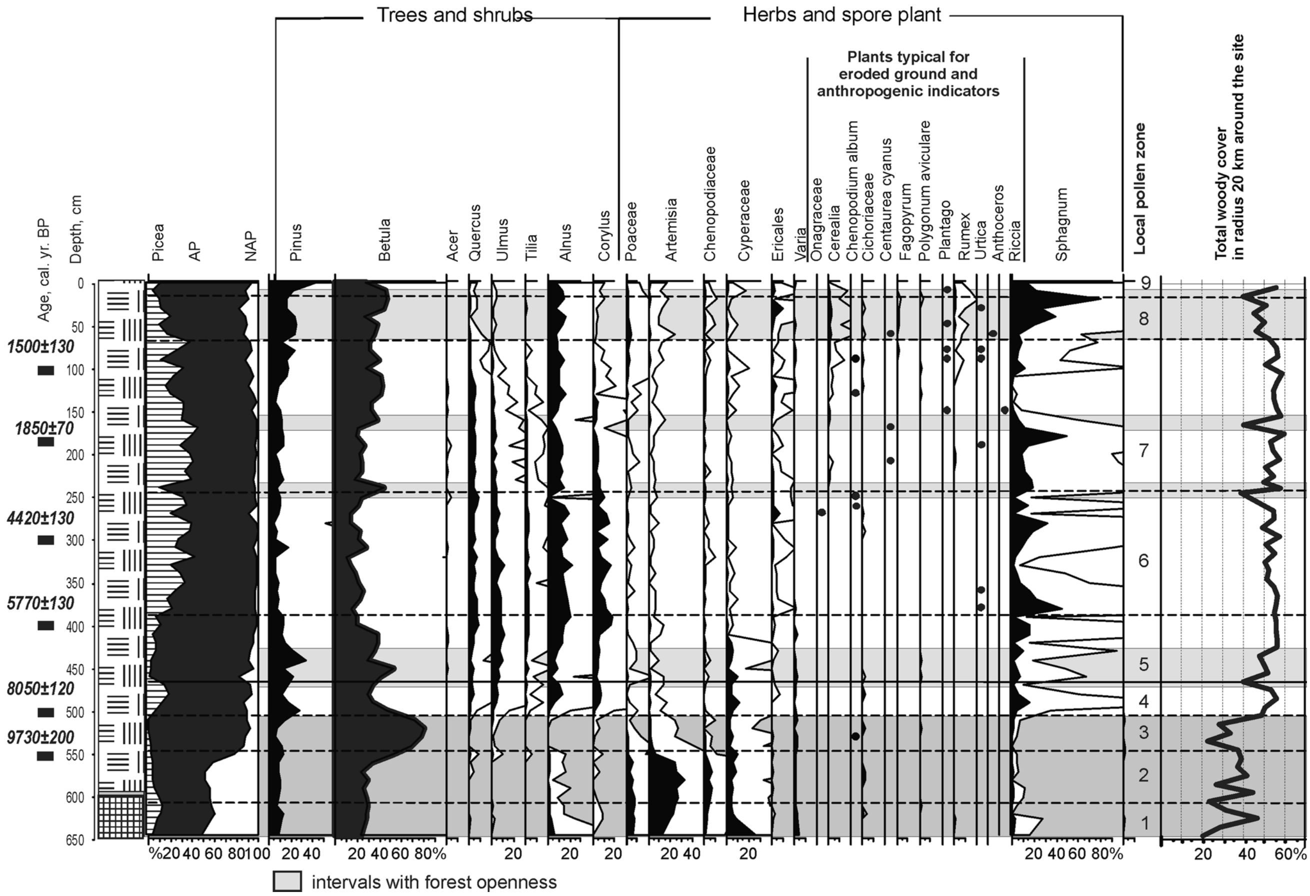

Fig. 6 Pollen diagram of Staroselsky moch mire and reconstruction of total tree cover within a radius of 20 km around the borehole

forest. By this time, the area had been occupied for at least several centuries by East Slavic tribes, who expelled and assimilated the Ugro-Finnic population. The land around the Staroselsky Moch mire was probably inhabited, but there is no archaeological background for this hypothesis. The pollen spectra are characterized by high values of *Betula* pollen, while values of *Picea* and broad-leaved trees decrease significantly. Presence of Cerealia together with pollen of weeds (*Centaurea, Chenopodium album, Polygonum aviculare, Urtica* and *Rumex*) indicates farming. There was a decrease in woody cover at about 1,800 cal. B.P. suggesting a link between landscape openness and human influence.

According to available data on land use in central Russia, the greatest human activity in Tver' region occurred in the second half of the 18th century (Borisenkov and Pasetskii 2002). The role of arable land and hay meadows reached the highest level. This period in the pollen spectrum of the Staroselsky Moch profile is characterized by maximum concentration of crop plants and high values of *Plantago, Rumex, Chenopodium album, Polygonum aviculare* and *Urtica* (PAZ 8, depth 10–60 cm). The proportion of woodland cover significantly decreased. The potential limit for agricultural expansion was reached in the 19th century and after that agriculture in the area fell into decay as the process of wetland development became more active. The reconstruction of total woody cover inferred from pollen assemblages of the uppermost 10 cm of the peat deposits (PAZ 9) indicates an increase of woodland areas up to 70 %. Nowadays clear cutting within the reserve is prohibited and woodlands are extensive.

The changes in tree cover in the area of the reserve before the first appearance of human indicators in pollen spectra were caused by climatic changes only, whereas during the last 4,000 years, they were induced both climatic and human factors. According to available data, there is no evidence of natural processes which could have led to a long-term significant decrease of tree coverage in the central part of the East European plain during the late Holocene (Khotinsky 1993; Novenko et al. 2009b).

Reconstructions of vegetation and human impact in the forest-steppe zone (the Kulikovo Battlefield area)

The pollen sequence of the Podkosmovo mire, new micro charcoal data and estimations of woody coverage of the

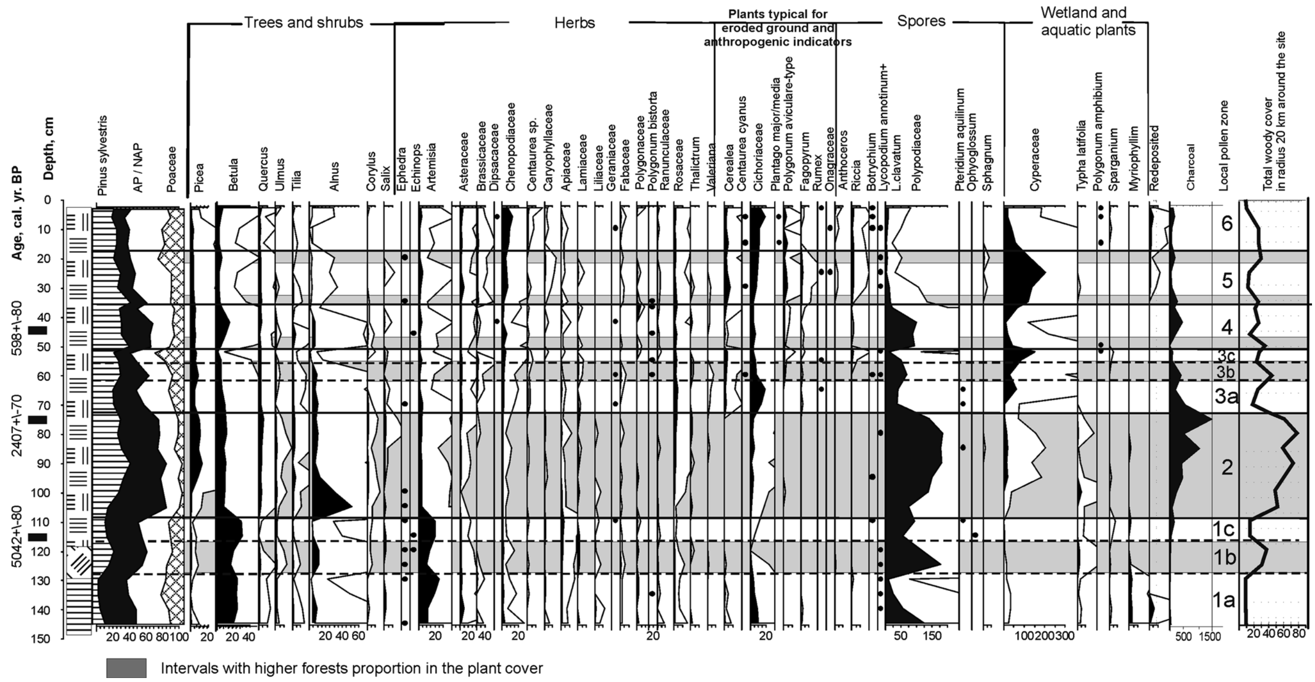

Fig. 7 Pollen diagram of Podkosmovo mire, micro-charcoal concentration and reconstruction of total woody cover within a radius of 20 km around the borehole

Kulikovo Battlefield area give us the possibility to reconstruct a history of human–environment interactions during the mid- and late Holocene.

The composition of pollen assemblages in the Podkosmovo profile (LPAZ1, depth 108–150 cm, Fig. 7) reflects a steppe vegetation for the second part of the late Atlantic—early Sub-boreal (7,000–6,000 to 5,000–4,500 cal. B.P.). The *Artemisia*-dominated communities with Poaceae and Chenopodiaceae as co-dominants include typical steppe elements (*Ephedra*, *Echinops*), as seen not only in the Podkosmovo mire pollen assemblages, but also in the pollen assemblages of Berezovskoye mire, 2 km south-east from the Podkosmovo mire (Novenko et al. 2012), and other sections in the river Don basin and its tributaries (Novenko et al. 2009a; Folomeev et al. 1990). According to the reconstructions of total woody cover in a 20 km radius around Podkosmovo mire, arboreal vegetation occupied about 10 % of the area, which is typical for a modern steppe zone (Bartalev et al. 2011). During the period from 6,000 to 5,000 cal. B.P., the area covered by woodlands increased up to 20–25 %. Patches of *Pinus-Betula* woodlands with broad-leaved trees became more widespread, as did *Alnus* on wetter ground.

Archaeological records (Folomeev et al. 1984, 1990; Gonianyi et al. 2007; Khotinsky 1993) indicate that the floodplains of the river Don and its tributaries in the Kulikovo Battlefield area were settled, starting in the early Neolithic. According to archaeological findings the period of local Neolithic occupation was about 7,300–5,400 cal. B.P. (Folomeev et al. 1984). Neither pollen nor micro-charcoal records show evidence of extensive agriculture. Disturbance of the plant cover and human-induced fires as human impact on vegetation during the Neolithic was primarily very local (Novenko et al. 2012). Apparently, the small proportion of tree cover could be the result of climatic conditions.

Changes in pollen assemblages at 4,500 cal. B.P. (LPAZ 2, depth 70–108 cm, Fig. 7) reflect a rapid expansion of woodlands in the upper river Don basin due to climatic cooling and increasing wetness. The proportion of woods in the vegetation cover grew up to 30 %. During the period 4,500–2,400 cal. B.P., pine woods with an admixture of *Quercus, Tilia, Ulmus* and *Alnus* occupied the area of the Kulikovo Battlefield. The meadow steppe communities probably survived only on dry slopes and well-drained watersheds. The share of woodlands in plant cover varied from 30 to 40 % and at 2,700 cal. B.P. it reached 45 %, showing the existence of a forest-steppe landscape. The other important features of peat horizons of the Podkosmovo fen forming in the Sub-boreal is a significant number of micro-charcoal fragments, which are considered a good proxy for higher fire incidence and/or human impact (Power et al. 2008). Compared to the previous phase, the amount of micro-charcoal in samples is an order of magnitude higher (Fig. 7), probably due to higher frequency of fires on the adjacent land. A comparison of the total woody cover values inferred from pollen data with the micro charcoal content in the peat shows a good agreement between these curves (Fig. 7). The charcoal production strongly depends on vegetation type (Patterson et al. 1987). Treeless steppe vegetation during the Atlantic period was too open to carry frequent or intense fires. The concentration of micro-charcoal is about 50–100 particles/cm^3. Increasing woody cover was accompanied by a growth in charcoal concentration (500–1,500 particles/cm^3), as wood burning was obviously a source of micro-charcoal remains detectable in pollen slides.

Archaeological data suggests that predominantly nomadic herdsmen were present in the Kulikovo Battlefield area in the Bronze Age, about 4–5 ka B.P. (Krasnov 1999). They settled vast floodplain meadows, including a settlement adjacent to the Podkosmovo mire (Novenko et al. 2012). However, the Bronze Age sites in the area of the Kulikovo Battlefield have not yet been investigated in detail. Pollen assemblages from our profile suggest some human-induced modifications of landscape during this period. The spectra include several taxa regarded as indicative of communities disturbed by human activities and rare Cerealia. Because humans were present for short periods in the area, during the Bronze Age, human-induced changes in the vegetation remained small and local.

A dramatic change of vegetation in the area occurred at 2,400 cal. B.P. Pollen spectra of this time are characterized by decreased AP values while *Artemisia*, Poaceae, Asteraceae and Cyperaceae tend to increase (see PAZ 3, depth 50–70 cm, Fig. 7). The areas covered by woodland reduced significantly to 15 %. The micro-charcoal data reveal that the degradation of woodland followed the highest peak of charcoal concentration, suggesting that burning was facilitated by times of climate change and environmental instability (Black and Mooney 2006). The transition between vegetation types and high incidence of fires at 2,400 cal. B.P. was probably caused by both climatic factors and human impact. Long-term studies of surface soils and buried palaeosols of the Kulikovo Battlefield area (Aleksandrovskii and Chichagova 1998) and pollen data (Novenko et al. 2012) show a noticeable decrease in annual precipitation at this time. Besides, pollen of cultivated cereals and *Fagopyrum esculentum* (buckwheat) is present. Plant communities of the areas adjacent to the mire included pioneer taxa that are typical of disturbed habitats and agricultural land. The indicators of these habitats (*Plantago major/media*, *Rumex*, *Polygonum aviculare*, *Centaurea cyanus*, *Urtica,* Onagraceae and Hepaticae) become frequent in pollen assemblages. Although archaeological findings of the early Iron Age are scarce in the area of the Kulikovo Battlefield and this period is not well studied, we have clear evidence of human disturbance of woodlands.

During the Middle Ages, the Kulikovo Battlefield area was repeatedly occupied and abandoned. The upper river Don basin hosted Slavic settlements in the 9th and mid-10th centuries A.D., and more than 250 Old Russian settlements are known, belonging to two periods, late-12th to mid-13th, and 14th century A.D. For about 200 years between the last quarter of the 14th century and the early 17th century A.D., the Kulikovo Battlefield area was uninhabited (Gonianyi et al. 2007). Reconstruction of total woody cover during the last millennium (depth 0–55 cm, Fig. 7) shows a significant decrease of woodland cover in the periods of human occupation. In the period when the area was abandoned, the woodlands in the areas recovered. It has to be mentioned that the uncertainties in radiocarbon dating make precise correlation difficult. Pollen spectra corresponding to phases of landscape openness demonstrate higher pollen values of crop plants, weeds and plants that are typical of bare soil (Fig. 7). Often the peaks in the curve of Cerealia pollen follow peaks in micro-charcoal concentration that can be explained by an extension of slash-and-burn cultivation.

Historical sources show that the 17th century, when the population density greatly increased and watersheds were ploughed, marked a turning point in human-environment relationships (Novenko et al. 2012). Natural vegetation communities were gradually destroyed and transformed into an agricultural landscape. The estimates of woody coverage during the last four centuries indicate some fluctuations in proportion of woodlands and grasslands within the Kulikovo Battlefield area. A degradation of woodlands in the 20th century is clearly shown in our reconstructions. Nowadays woodlands occupy no more than 10 % of the area.

Conclusions

The present research is aimed at assessing Holocene woody cover densities and woodland disturbance in European Russia, using analogue-based methods of quantity reconstructions and an innovative approach, which combines modern pollen datasets with remotely sensed data. The accuracy of regional woody cover reconstructions was tested by the leave-one-out cross-validation method. The validation results showed that the applied method is sufficient for reconstruction of major changes of woodland vegetation in past times. Application of the BMA technique to pollen data from the two key regions in the central part of European Russia have demonstrated that the changes in regional woody cover seem to be a good tool for reconstruction of human disturbance during the prehistoric period. In the present studies we used a 20 km radius as the first attempt for the Holocene woodland cover reconstructions based on pollen data and MODIS satellite images. The obtained results show that an area of this size corresponds well for description of vegetation disturbance in a regional framework. Nevertheless, experiments are in progress with reconstruction of woodland cover with other radii (2, 5, 10 and 50 km).

Evidence of several phases of short-term human occupation in the south of the Valdai upland, in the zone of the mixed coniferous-broadleaved forest, in the last 4,000 years has been provided by reductions of total woody coverage and changes in pollen spectra. Although there are no archaeological data from the study area, there is a great potential for archaeological research in this region. A significant decrease in woody cover proportion in the south of the Valdai upland is reconstructed in the 18th–19th centuries A.D., suggesting a linkage between landscape openness and human influence.

The high biodiversity of the forest-steppe area made the upper river Don basin very attractive for early human populations. Signs of human-induced changes in the vegetation and fires are clearly pronounced in the pollen and micro-charcoal records in the Neolithic and Bronze Ages, however human impact on plant cover was not significant until 2,400 cal. B.P. Reconstructions of total woody cover show a good agreement with land-use history of the area. Extensive agriculture during the periods of human occupation resulted in a decrease in woodland cover, but when the land was abandoned, woods recovered there. Large-scale landscape changes and the degradation of natural vegetation occurred in the medieval period and become conspicuous over the last two centuries.

Acknowledgments This work was supported financially by the Russian Fund for Basic Research (projects 11-05-00557 and 12-05-31098). Our sincere thanks go to Logan Berner for critical reviewing of the manuscript and help with the English language.

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