Estimation of potential and actual evapotranspiration of boreal forest ecosystems in the European part of Russia during the Holocene

A Olchev\textsuperscript{1} and E Novenko\textsuperscript{2}

\textsuperscript{1} A N Severtsov Institute of Ecology and Evolution of RAS, Leninsky Prospect 33, Moscow, Russia
\textsuperscript{2} Institute of Geography of RAS, Moscow, Russia

E-mail: aoltche@gmail.com

Received 10 June 2011
Accepted for publication 3 November 2011
Published 29 November 2011
Online at stacks.iop.org/ERL/6/045213

Abstract
A simple regression model for calculating annual actual evapotranspiration (ET) and potential evapotranspiration (PET), as well as annual transpiration (TR) of mature boreal forests grown in the European part of Russia in the Holocene using paleoclimatic and paleobotanical data (air temperature, precipitation, forest species compositions) is presented. The model is based on nonlinear approximations of annual values of ET, TR and PET obtained by the Levenberg–Marquardt method using the results of numerical simulations of ET, TR and PET provided by a process-based Mixfor-SV AT model for forests with different species compositions under various thermal and moistening conditions. The results of ET, TR and PET reconstructions for the Holocene show large variability and high correlation with the air temperature pattern. Minimal values of ET and PET are obtained for the Younger Dryas cold phase (11.0–10.0 \textsuperscript{14}C kyr BP) when ET varied between 320 and 370 mm yr\textsuperscript{-1} and PET varied between 410 and 480 mm yr\textsuperscript{-1}. During the Late Atlantic periods of the Holocene (4.5–5.1 \textsuperscript{14}C kyr BP), ET and PET reached maximal values (ET: 430–450 mm yr\textsuperscript{-1} and PET: 550–570 mm yr\textsuperscript{-1}).

Keywords: actual and potential evapotranspiration, transpiration, boreal forest ecosystems, paleoclimatic reconstructions, regression model, Mixfor-SVAT model

Introduction

Analysis of long-term variability of climatic conditions (Schmidt et al 2004) and vegetation cover (Prentice et al 1996, Seppa et al 2004, Viau and Gajewski 2009, Novenko et al 2009b, Kleinen et al 2011) in the boreal forest zone of Northern Eurasia in the Holocene shows a very high sensitivity of forest ecosystems to climate changes. Forest responses to climate are mainly manifested in changes of forest structure and species composition. Periods with warm climate are generally characterized by the expansion of broadleaf species to the north, whereas in periods with a colder climate the boundary between the natural habitats of coniferous and broadleaf species shifted to the south (Velichko 2010).

The migration rate of tree species in the boreal zone under climatic changes during the Holocene was relatively low. According to pollen, plant macrofossil and radiocarbon data of Holocene deposits in Europe summarized by Huntley and Birks (1983) the maximal migration rate of broadleaf tree species to the north during the Holocene did not exceed 200–300 m yr\textsuperscript{-1}. In the short-term perspective (50–100 yr) the climatic influence is mainly manifested in partial changes of proportions of spruce and broadleaf species in forest stands (Novenko et al 2009b, 2009a). Abrupt changes
of species composition in forests may have occurred after forest fires, anthropogenic impacts (e.g. clear-cutting) or forest damage/destruction due to insect attacks or any anomalous weather events (e.g. drought, windthrow) (Chapin et al 2004). Information on the sensitivity of different forest types to climatic changes in the past can obviously be very useful both to explain forest dynamics in past epochs and also to improve our ability to predict the potential impacts of future climatic change on boreal forest ecosystems.

A high correlation between changes of climate and vegetation is widely used in paleogeography for reconstructions of climatic parameters, e.g. temperature of warmest and coldest months, mean annual temperature and annual precipitation rate (e.g. Klimanov 1984, Davis et al 2003, Mayewski et al 2004, Velichko et al 2008). Accurate climatic reconstruction requires detailed studies of the long-term variability of vegetation cover and its response to changes of the thermal and moisture conditions of land surface areas (Velichko 2010). The moisture conditions of the area are usually described using data on precipitation, PET and ET of a land surface. The aridity index determined as the ratio of annual precipitation to PET is a very popular numerical indicator to characterize the degree of dryness of the climate on some surface area (Budyko 1974). In some studies the evaporation ratio calculated as a ratio of ET to precipitation is also used (Tchebakova et al 2009).

For estimation of the PET of a land surface under modern conditions the different modifications of the Penman (1948) or the Priestley–Taylor equations (Priestley and Taylor 1972) are usually applied. Penman defines the PET as evaporation from an open water surface, wet vegetation or bare soil (Penman 1948). The calculation procedure of PET requires meteorological parameters e.g. net radiation, air temperature, air water vapor deficit, wind speed, which presently can be very easily measured under field conditions. The application of these approaches for reconstructions of the PET of the area from paleo-data is however very inconvenient because the methods require meteorological data as input, e.g. net radiation of the land surface or wind speed that obviously cannot be exactly determined using existing methods of proxy data analysis.

Thornthwaite’s approach for estimation of PET (Thornthwaite 1948) assumes that the mean daily PET under well-watered soil conditions is proportional to the mean surface air temperature and the length of daylight (Thornthwaite and Mather 1957). Thornthwaite defines PET as the water loss which will occur if there is no deficiency of water in the soil for use by vegetation. It is obvious that the Thornthwaite formulation of the PET is not equal to the Penman formulation. However, Mintz and Walker (1993) compared the PET estimations provided by the Thornthwaite method with PET calculated by the Priestley–Taylor equation (Priestley and Taylor 1972) for several types of land surface and showed very good agreement between them.

The methods for estimation of ET from proxy data are usually based on relatively simple approaches considering the ET as a function of PET (derived from climatic variables reconstructed from pollen and plant macrofossil data) and parameters characterizing the moisture status of the area (e.g. Prentice et al 1996, Ward et al 2007). The clear advantage of the method is the small number of required input parameters. The disadvantage of the method is that it ignores the natural variability of biophysical properties of different vegetation types controlling the plant water uptake and TR rates (e.g. Wilson et al 2002, Oltchev et al 2002a, Korzukhin et al 2008), which can obviously significantly reduce the accuracy of ET calculations.

An alternative approach to reconstructing the PET and ET of the boreal forest zone in the Late Pleistocene was proposed by Velichko et al (2008) and Velichko (2010). The method is based on the analysis of modern ranges of climatic and hydrological conditions (including ET and PET) for the areas where the tree species grow whose pollen and plant macrofossils have been found in Late Pleistocene sediments (Grichuk et al 1984). The climatic and hydrological parameters of the regions in which the majority of the recorded species grow together nowadays, are considered as reconstructions of the past epochs. It should be mentioned however, that this method has several serious restrictions for its practical application, such as the difficulty of finding relatively small areas where the different components of fossil flora grow together at the present time.

Within the framework of this study simple regression models to estimate ET, PET and TR rates will be suggested. The main advantage of the method is that it allows the estimation of ET, PET and TR taking into account the air temperature, precipitation and species composition of the forest canopy. The regression equations will be applied to describe the temporal variability of the annual ET, PET and TR rates of mature boreal forests grown in the southern part of the Valday hills area (55°–58°N, 32°–33°E) at the southern boundary of the boreal forest community in European Russia in the Holocene. Air temperature, precipitation and species compositions of the forest during the Holocene will be reconstructed from available paleobotanic data for the study area (Novenko et al 2009b, 2009a). The coefficients in the regression model will be determined from statistical analysis of the results of modeling estimations of ET, PET and TR provided by a process-based Mixfor-SVAT model (Oltchev et al 2002a, Oltchev et al 2009).

1. Mixfor-SVAT description

Mixfor-SVAT is a one-dimensional process-based SVAT model for the description of sensible heat, H₂O and CO₂ exchange between horizontaly uniform and vertically structured mono- and multispecies forest stands and the atmosphere (Oltchev et al 2002a, Oltchev et al 2008, 2009). It is based on the aggregated description of the physical and biological processes occurring in a forest ecosystem at leaf, tree and entire ecosystem level. The model consists of several closely coupled sub-models describing: radiative transfer within a forest canopy; turbulent transfer of sensible heat, H₂O and CO₂ within and above a forest canopy; transpiration, root water uptake, leaf and stem water storage; precipitation interception and evaporation; soil surface evaporation; photosynthesis,
heterotrophic and autotrophic respiration of soil and plants; heat and water transfer in soil (figure 1).

The forest canopy in the model is represented as an ensemble of individual trees of different species which are evenly distributed within the homogeneous ground surface area. It is assumed that there are no differences between structural and biophysical properties of trees of the same species (i.e. each tree of the same species is characterized by the same height, leaf and plant area indexes, root depth, maximal stomatal conductance, photosynthesis and respiration rates, etc).

The calculation procedure of the total ecosystem heat and H$_2$O fluxes is based on the combined solution of radiation, heat and water balance equations for individual trees, soil and the entire forest ecosystem. The time step of the model is 1 h. It allows one to simulate both annual and daily dynamics of H$_2$O and CO$_2$-exchange in a plant canopy taking into account a non-steady-state transfer of water inside the trees.

Canopy evapotranspiration is parameterized as a function of the canopy microclimatic conditions (air temperature and humidity, wind speed, global radiation, CO$_2$ concentration) and biophysical properties of the forest stand. It includes the evaporation of intercepted rain water (IR) and TR of the trees of different species and understory. Leaf stomatal conductance is considered as a key parameter regulating H$_2$O and CO$_2$ exchange between the intercellular space of leaves and the ambient air. In the model this is influenced by species-specific properties, ambient meteorological conditions and the water status of the leaves. Leaf water status is determined by the available water stored in the different tree organs, xylem conductivity and the soil moisture content in the root zone.

To describe the multispecies structure of the forest stand, the model uses both species-specific and species-averaged input parameters. For the description of the processes occurring inside an individual leaf or tree (e.g. TR, water uptake, water storage, photosynthesis, respiration) Mixfor-SVAT uses individual species-specific input parameters. For the description of exchange processes between different tree species within each sub-layer, as well as for the description of the processes on the ecosystem scale (e.g. turbulent exchange, radiative transfer) it uses species-averaged parameters. Such an approach allows the description in the model of both entire ecosystem H$_2$O and CO$_2$ fluxes and flux partitioning among different tree species and canopy layers in the forest stand.

Mixfor-SVAT was validated using the results of long-term flux measurements in different types of forest ecosystems. The results of model validation show that Mixfor-SVAT describes the annual and daily patterns of CO$_2$ and H$_2$O fluxes under different climatic and soil moisture conditions very well (Oltchev et al. 1996, 2002a, Falge et al. 2005, Oltchev et al. 2008).

2. Regression model for reconstruction of PET, ET and TR of forest ecosystems

For the parameterization of annual ET, PET and TR, three key parameters obtained during paleoclimatic and paleobotanical reconstructions (mean annual air temperature, annual precipitation and proportion of coniferous and deciduous trees in a forest stand) were selected. The coniferous and deciduous tree species growing in the European territory of Russia are characterized by different phenological, structural and ecophysiological properties. The trees differ considerably in the time of leaf flushing and leaf fall, as well as in the duration of the growing season. Their leaves, crowns, trunks and root system have various structures and morphology. They are characterized by different responses of leaf stomata to change of ambient conditions. The xylem of the trees has different conductivity and water storage capacity. All these factors result in a very strong difference in annual patterns of
the ET, TR and PET between forest types with different species composition.

In order to analyze the sensitivity of the ET, TR and PET to changes of selected input parameters (mean annual air temperature, annual precipitation and forest species composition) the data set including annual ET, TR and PET rates modeled by Mixfor-SVAT for forests with different species composition (six types from monospecific spruce to mixed and monospecific deciduous forest stands) and for all possible ranges of climatic conditions (including all possible combinations of mean annual temperature and precipitation rates) that can be observed in the study area at present and in the past epochs was created.

The possible ranges of temperature and precipitation variability in the past epoch in the southern part of the Valday hills area were determined from analysis of long-term meteorological data sets (Desherevskaya et al 2010) and proxy-based paleoclimate reconstructions (Novenko et al 2009a, Velichko 2010). It was found that during the Holocene the mean annual temperature ranged from 0 to 8°C, and the annual precipitation from 300 to 800 mm yr\(^{-1}\).

To generate annual trends of air temperature and precipitation the results of continuous meteorological measurements (temperature and humidity of air, precipitation, wind speed, global solar radiation) carried out in the forests of the Central Forest State Natural Biosphere Reserve (CFSNBR, 56°30’N, 32°50’E) since 1998 (Schulze et al 2002) were used. The basic measured trend of meteorological parameters 54 possible annual trends of air temperature and precipitation were generated. They include all possible combinations of mean annual air temperatures and precipitation rates for the study area. The time step of meteorological parameters in each data set is 1 h. It was assumed that the annual patterns of solar radiation, wind speed and water vapor deficit were the same for all data sets. Thus, possible changes of air humidity under changes of air temperature were taken into account.

In the next step, TR and ET of six types of model forest stands with a various proportion of spruce and deciduous (birch, aspen, linden, maple) tree species were modeled by Mixfor-SVAT for each generated annual trend of meteorological parameters. Annual PET was calculated by the Priestley–Taylor equations using the mean daily vegetation temperatures and net radiation values derived by Mixfor-SVAT. All necessary model input parameters describing biophysical properties of different tree species and soil were determined during intensive field campaigns at several experimental sites in the southern part of Valday hills as well as taken from literature (Olchev et al 2002a, 2002b, Korzukhin et al 2008).

In the last step the mean annual values of TR, ET and PET for various combinations of annual temperatures and precipitation rates, and for forest stands with various species composition were calculated. Forest composition in the model was described by a parameter characterizing the proportion of spruce trees in a forest stand. It ranges from 0 (monospecific deciduous forest) to 1 (monospecific spruce forest).

The resulting data set (324 cases) was used for the analysis of the sensitivity of TR, ET and PET to changes of input parameters (figures 2 and 3) as well as for estimation of the unknown parameters of the regression models (equations (1)–(3)).

Analysis of the response of modeled ET, TR and PET to changes in the air temperature, precipitation and species composition of forest stands show a very high sensitivity of ET, TR and PET to changes of air temperature and species composition of forest stands (figure 2), as well as a moderate sensitivity of ET to changes of annual precipitation (figure 3). The effect of precipitation changes on TR is relatively low and it is visibly manifested only with very small values of annual precipitation (lower than 400 mm yr\(^{-1}\)) and only for stands with a large proportion of spruce trees when the deficit of available soil water in the rooting zone significantly reduced the root water uptake and the transpiration rate of the trees.

To parameterize ET, TR and PET, a nonlinear multiplicative function assuming dependence of ET, PET and TR on air temperature, precipitation rate and proportion of spruce trees in a forest stand is used. The type of function (linear or quadratic) for adjustment factors describing the influence of air temperature, precipitation and tree species composition is chosen taking into account the results of sensitivity analysis of ET, PET and TR (figures 2 and 3). To describe the dependence of ET and TR on air temperature a quadratic type of function is used whereas the dependence of ET and TR on precipitation is parameterized by a linear function. The dependence of ET and TR on the proportion of spruce trees in a mixed forest stand is also parameterized by a quadratic function that allows the description of e.g., the higher ET and TR for the mixed (spruce–deciduous) forest in comparison with monospecific spruce or deciduous ones of the same tree age, biomass, height, etc (Olchev et al 2009).

In the general form the equations for the estimation of annual ET, PET and TR rates of a boreal forest ecosystem are written as:

\[
ET = ET_0(a_1(T/T_M)^2 + a_2T/T_M + a_3) \\
\times (a_4N^2 + a_5N + a_6)(a_7(P/P_M) + a_8) \\
(1)
\]

\[
TR = TR_0(a_1(T/T_M)^2 + a_2T/T_M + a_3) \\
\times (a_4N^2 + a_5N + a_6)(P/P_M + a_8) \\
(2)
\]

\[
PET = PET_0(a_1(T/T_M) + a_2)(a_3N + a_4) \\
(3)
\]

where ET\(_0\), TR\(_0\) and PET\(_0\)—the minimal values of ET, TR and PET of the area observed in the Late Glacial period (ET\(_0\) = 340 mm, TR\(_0\) = 180 mm and PET\(_0\) = 460 mm), T—mean annual air temperature in degrees Celsius, T\(_M\)—mean annual air temperature of the study area under current climatic conditions (T\(_0\) = 5°C, Desherevskaya et al 2010), P—annual precipitation amount in millimeter, P\(_M\)—mean annual precipitation of the study area under current climatic conditions (P\(_0\) = 700 mm) N—proportion of spruce trees in a forest stand (ranged between 0 and 1), a\(_1\)–a\(_8\)—empirical coefficients. The coefficients a\(_1\)–a\(_8\) in the equations were obtained using the Levenberg–Marquardt method from statistical analysis of a data set including information about the ET, PET and TR of forests with different tree species composition for different combinations of annual air temperatures and annual precipitation rates (table 1). The confidence interval for parameter estimates was 95%.

The proportion of variability in the data set that was accounted for by the regression models (coefficient of
Figure 2. Dependence of the ET, TR and PET (mm yr\(^{-1}\)) rates on mean annual air temperature and proportion of spruce in a mixed (spruce–deciduous) forest stand growing in well-drained soils in temperate moderately continental climate in the central part of European Russia. ET, TR and PET are modeled by Mixfor-SVAT. Isolines of ET, TR and PET are plotted for annual precipitation amount of 500 mm.

![Dependence of ET, TR and PET on mean annual air temperature and proportion of spruce in a mixed forest stand](image)

Table 1. Values of empirical coefficients (\(a_1\)–\(a_8\)) for estimation of annual ET, TR and PET with equations (1)–(3).

| Parameters | \(a_1\) | \(a_2\) | \(a_3\) | \(a_4\) | \(a_5\) | \(a_6\) | \(a_7\) | \(a_8\) |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|
| ET         | −0.0239 | 0.4142 | 1.9603 | −0.1066 | 0.0652 | 0.6174 | 0.0350 | 0.8549 |
| TR         | −0.0078 | 0.4945 | 1.5558 | −0.3404 | 0.3414 | 0.7924 | −0.0039 | 0.8882 |
| PET        | 0.2031  | 1.1514 | 0.0833 | 0.8623 | —      | —      | —      | —      |

The coefficient of determination, \(r^2\), is relatively large for PET and ET (\(r^2 = 0.994\) for PET and \(r^2 = 0.987\) for ET). The coefficient of determination for TR was some lower (\(r^2 = 0.912\)). This can be explained by the simplicity of the regression models we used.

For reconstruction of PET, ET and TR of forest ecosystems of the European part of Russia in the Holocene it is assumed that the tree age of the modeled monospecific and mixed forests is more than 60 yr (mature and over mature stands), their leaf area index (LAI) is not less than 4, and that they grow on well-drained soils. It is also assumed that the biophysical responses to the climate (e.g. maximal stomatal conductance and response functions of stomatal conductance to changes of environmental parameters) of the different tree species comprising the forest stand in past periods of the Holocene are the same as at present.

Applicability of the suggested regression equations for calculations of ET, PET and TR is generally limited by the area for which the biophysical parameters (leaf stomatal conductance, responses of leaf stomata to change of ambient conditions, leaf photosynthesis and respiration rates, leaf and tree water capacity, tree xylem conductivity, etc) regulating the \(\text{H}_2\text{O}/\text{CO}_2\) exchange between selected tree species (birch, aspen, linden, maple) and ambient air were determined. It is obvious that the properties of each individual tree species are strongly dependent on many different factors (such as position of trees in forest stands, tree age, soil morphology, soil nitrogen availability, air pollution level, etc) and they can differ from the
properties of other tree species as well as from the properties of the same species growing under different conditions. Thus, it is necessary to take into account that application of these equations to determine ET, PET and TR for forests growing in regions outside the study area and/or represented by other tree species can result in some uncertainties in flux estimations.

3. Vegetation and climate variability of the southern part of the Valday hills area in the Holocene

The paleoenvironmental and paleoclimatic reconstructions in the study are based upon pollen, plant macrofossil and radiocarbon data from three profiles of modern raised bogs located in the CFSNBR in the southern part of the Valday hills (Novenko et al. 2009b, 2009a). The paleoclimatic parameters of the Holocene (temperature of warmest and coldest months, mean annual temperature and precipitation) were derived using the information-statistical method suggested by Klimanov (1984). The method is based on correlation analysis of sub-recent pollen spectra, present vegetation structure and local climatic conditions. It assumes that the per cent proportions in modern surface pollen assemblages are closely linked with some climatic parameters such as air temperature and precipitation amount. The method is based on a multi-dimensional regression model describing every surface pollen assemblage as a function of climatic variables. Parameters of the regression model are usually derived from the comparative analysis of spatial patterns of modern natural habitats of different tree species and climatic conditions corresponding to these habitats. The method was calibrated using pollen spectra taken from 800 profiles in different areas of Northern Eurasia (Klimanov 1984) and used for reconstruction of climatic condition of different time intervals in the Holocene (Velichko 2010). The mean statistical errors for the reconstructions using this method are: ±1°C for the mean annual, summer and winter temperatures and ±50–100 mm for annual precipitation (Klimanov 1984).

The reconstructions show that long-term temperature fluctuations and vegetation patterns clearly agree with the main phases of the Late Glacial and Holocene described in scientific publications (e.g. Mayewski et al. 2004, Velichko et al. 2008, Velichko 2010). The Late Glacial phases, the interstadial Allerød (11.8–11.0 14C kyr BP) and the stadial Younger Dryas (11.0–10.0 14C kyr BP) show distinct trends in the reconstructed mean annual temperatures (see figure 4). The vegetation cover during the beginning of the Holocene—Preboreal and Boreal periods (10.0–8.0 14C kyr BP) was mainly represented by birch forests (Novenko et al. 2009b). At the end of the Boreal period the area of the southern part of the Valday hills is characterized by a rapid expansion of mixed coniferous broadleaf forest with oak, linden, ash and elm. Climatic reconstructions suggest significant temperature fluctuations in the Early Holocene. The differences of the mean annual temperature between the cold and warm phases reached 4–6°C (see figure 4). The plant cover of the Atlantic phase (8.0–4.5 14C kyr BP) is characterized by the highest amount of broadleaf trees in the forest stands. The Late Atlantic (4.5–5.1°C kyr BP) appears to be the warmest phase of the Holocene, when the mean annual temperature rose to 4–6°C (up to 2.0°C above modern climatic conditions) (see figure 4).

The cooling period that followed after the Holocene optimum is characterized by an increase of the proportion of spruce (Picea abies) in the forest composition, and by the

Figure 3. Dependence of ET and TR (mm yr⁻¹) rates on annual precipitation and proportion of spruce in a mixed (spruce–deciduous) forest stand growing in well-drained soils in temperate moderately continental climate in the central part of European Russia. The ET and TR are modeled by Mixfor-SVAT. Isolines of ET and TR are plotted for a mean annual temperature of 4°C.
Figure 4. Paleo-reconstructions of species compositions (upper graph, Novenko et al. 2009a, Olchev et al. 2009), air temperature (middle graph), ET, PET and TR (lower graph) of the southern part of the Valday hills in European Russia in the Holocene. Temperature and precipitation in the Holocene were reconstructed using the Klimanov method (Klimanov 1984). Reconstruction of ET, PET and TR patterns were provided by the regression models. Phases of the Holocene and the Late Glacial: Al—Allerød, YD—Younger Dryas, PB—Preboreal, BO—Boreal, AT—Atlantic, SB—Subboreal, SA—Subatlantic, LIA—Little Ice Age.

Several warming and cooling periods in the second part of the Holocene have also been identified. Warm phases correspond to the Middle Subboreal (at ca. 3.5 14C kyr BP), the Early Subatlantic (at 2.5 14C kyr BP) and the Medieval Warm Anomaly (MWA, 9th–12th centuries AD). The deviation of the mean annual temperatures from their present values did not exceed 1 °C.

The most recent cold phase of the Holocene (the Little Ice Age, 15th–17th centuries AD) is characterized by a decrease of the mean annual temperature down to 2 °C. The proportion of the warmth-demanding broadleaf trees declines rapidly,

spreading of mires over the area. In the Subboreal (4.5–2.5 14C kyr BP) and Subatlantic (after 2.5 14C kyr BP) periods there is significant variability of species composition over time. Phases with spruce dominating the forests, typical for the taiga zone (the Early and the Late Subboreal, the Middle Subatlantic), alternated with phases of mixed coniferous broadleaf forests with high proportions of linden and elm (the Middle Subboreal, the Early and Late Subatlantic). The vegetation cover during the Late Subatlantic was mainly characterized by the spreading of secondary birch forests, probably induced by human impact.
oak disappears completely, and spruce forests and wetland ecosystems become widespread (Novenko et al. 2009a).

4. Reconstruction of PET, ET and TR of forest ecosystems in the Holocene

The results of ET, PET and TR calculations for different periods of the Holocene show that minimal values of ET and PET are obtained for the stadial Younger Dryas (11.0–10.0 14C kyr BP) when ET does not exceed 320–360 mm yr\(^{-1}\) and PET is about 420–440 mm yr\(^{-1}\). Annual TR is about 80% of ET and for the period it ranged between 170 and 190 mm yr\(^{-1}\). Thus TR significantly exceeds the sum of interception evaporation (IE—evaporation of rain water intercepted by the forest canopy) and evaporation from the understory and soil surface (UE). During the Younger Dryas time the forested area was strongly reduced, and the role of steppe (Artemisia-dominated) communities increased due to the onset of cold climate with low surface moisture (see figure 4).

In the warmest periods of the Holocene (4.5–5.1 14C kyr BP on the studied area) ET, TR and PET reached maximal values. ET was 430–450 mm yr\(^{-1}\), TR—260–280 mm yr\(^{-1}\) and PET—550–570 mm yr\(^{-1}\). In this period, the proportions of IE and UE in ET increased significantly and reached 45–50%.

This period is characterized by a low proportion of spruce in the forest stands (10–20%) and by a relatively high proportion of broadleaf tree species with some birch and aspen. The aridity index ranged between 1.0 and 1.2, optimal conditions for growing mixed spruce–broadleaf forest stands.

During the cooling period following the Holocene optimum, ET decreased slightly to 400–420 mm yr\(^{-1}\) and PET to 550–570 mm yr\(^{-1}\). The proportion of TR in ET was about 55%, i.e. close to values obtained for the Holocene thermal maximum. The aridity index during this period ranged between 1.2 and 1.6 which corresponds to the abundant moisture conditions of the area. Under relatively high annual precipitation ranging between 600 and 800 mm yr\(^{-1}\), the moistening of the area increased. This promoted an increasing presence of Picea abies (spruce) in the forest stands in some periods by as much as 70–80%. The proportion of broadleaf species at this time did not exceed 10–15%. Low evaporation and a relatively high precipitation rate can be considered one of the main reasons for the spreading of mires over the area.

In the warm phases of the Middle Subboreal, the Early Subatlantic and the Medieval warm periods, ET increased and reached 430–440 mm yr\(^{-1}\), TR—260–270 mm yr\(^{-1}\) and PET—550–560 mm yr\(^{-1}\). The aridity index varied between 1.1 and 1.3. During the cold phase of the Little Ice Age (15–17 centuries AD) ET decreased to 400–410 mm yr\(^{-1}\) and PET—510–520 mm yr\(^{-1}\). Annual TR for the period does not exceed 250 mm yr\(^{-1}\). The proportion of TR in ET increased to 60–65%. The aridity index varied around 1.3. Relatively cold and moist conditions promoted a further expansion of the spruce in the area whose proportion exceeded 80% at this time. Concurrently, conditions became adverse for broadleaf species. Their abundance declined significantly, and oak, as the most sensitive broadleaf species to soil over-moistening, generally disappeared from the area, and can be found only in plantations at present.

5. Conclusion

Results of model estimations of ET, TR, and PET during the Holocene using our regression models and the results of paleoclimatic and paleoenvironmental reconstructions show large variability of ET, TR, and PET that is mainly influenced by changes in air temperature and species composition of the forests. The effect of precipitation changes on ET and TR is relatively small and is manifested only when annual precipitation values are low (lower than 400 mm yr\(^{-1}\)) resulting in water stress in the rooting zone of the trees and closing of the leaf stomata in summer.

Minimal values of ET and PET are obtained for the Younger Dryas cold phase (11.0–10.0 14C kyr BP) when ET dropped to 320–370 mm yr\(^{-1}\) and PET to 410–480 mm yr\(^{-1}\). Annual TR for this period did not exceed 170 and 220 mm yr\(^{-1}\). During this period the study area was covered by a mosaic of vegetation including steppe and meadow communities with small patches of woodlands. The proportion of spruce in woodlands did not exceed 40% on average. In the warmest periods of the Holocene (4.5–5.1 14C kyr BP), ET, TR and PET reached maximal values (ET—430–450 mm yr\(^{-1}\), TR—260–280 mm yr\(^{-1}\) and PET—550–570 mm yr\(^{-1}\)). In this period, the forest consisted mainly of broadleaf tree species with an admixture of birch and aspen. The proportion of spruce in the forests did not exceed 10–20%. A decrease of ET (to 400–420 mm yr\(^{-1}\)) during the cooling period following the Holocene optimum, is accompanied by relatively high precipitation rates resulting in abundant moistening of the area, increasing presence of Picea abies (spruce) in forest stands, and the active process of mire development in the area.

The ET, TR and PET estimations in the forests of European Russia during the Holocene can be used to assess the effects of soil moisture availability on changes of species composition in a boreal forest community in different periods of the Holocene, and suggest plausible forest scenarios under projected future climate changes. The developed regression models can be also used for estimation of ET, TR, and PET of mature boreal forests with similar species composition growing in other geographical regions using available data of paleoenvironmental reconstruction.

Acknowledgments

This study was carried out within the frameworks of the Northern Eurasian Earth Science Partnership Initiative (NEESPI) and supported by grants of the Russian Foundation for Basic Research (RFBR 11-04-01622-a, RFBR 11-05-00557-a and RFBR 11-04-97538-p_center_a) and the program ‘Fundamental Bases of Biological Resource Management’ of the Russian Academy of Sciences (II.3).
