Change in Siberian Phytomass Predicted for Global Warming

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An equilibrium model driven by climatic parameters, the Siberian Vegetation Model, was used to estimate changes in the phytomass of Siberian vegetation under climate change scenarios (CO_2 doubling) from four general circulation models (GCM's) of the atmosphere. Ecosystems were classified using a three-dimensional climatic ordination of growing degree days (above a 5 °C threshold), Budyko's dryness index (based on radiation balance and annual precipitation), and Conrad's continentality index. Phytomass density was estimated using published data of Bazilevich covering all vegetation zones in Siberia. Under current climate, total phytomass of Siberia is estimated to be 74.1 ± 2.0 Pg (Petagram = 10^{15} g). Note that this estimate is based on the current forested percentage in each vegetation class compiled from forest inventory data. Moderate warming associated with the GISS (Goddard Institute for Space Studies) and OSU (Oregon State Univ.) projections resulted in a 23–26 % increase in phytomass (to 91.3 ± 2.1 Pg and 93.6 ± 2.4 Pg, respectively), primarily due to an increase in the productive Southern Taiga and Subtaiga classes. Greater warming associated with the GFDL (General Fluid Dynamics Laboratory) and UKMO (United Kingdom Meteorological Office) projections resulted in a small 3–7 % increase in phytomass (to 76.6 ± 1.3 Pg and 79.6 ± 1.2 Pg, respectively). A major component of predicted changes using GFDL and UKMO is the introduction of a vast Temperate Forest-Steppe class covering nearly 40 % of the area of Siberia, at the expense of Taiga; with current climate, this vegetation class is nearly non-existent in Siberia. In addition, Subboreal Forest-Steppe phytomass doubles with all GCM predictions. In all four climate change scenarios, the predicted phytomass stock of all colder, northern classes is reduced considerably (viz., Tundra, Forest-Tundra, Northern Taiga, and Middle Taiga). Phytomass in Subtaiga increases greatly with all scenarios, from a doubling with GFDL to quadrupling with OSU and GISS. Overall, phytomass of the Taiga biome (Northern, Middle, Southern, and Subtaiga) increased 15 % in the moderate OSU and GISS scenarios and decreased by a third in the warmer UKMO and GFDL projections. In addition, a sensitivity analysis found that the percentage of a vegetation class that is forested is a major factor determining phytomass distribution. From 25 to 50 % more phytomass is predicted under climate change if the forested proportion corresponding to potential rather than current vegetation is assumed.

Keywords phytomass, Siberia, climate change, global warming, carbon cycle, vegetation modeling, bioclimatology

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1 Introduction

We begin with the premise that significant global climate change induced by a buildup of greenhouse gases (e.g., carbon dioxide (CO_2), methane, chloroflourocarbons, nitrous oxide) in the atmosphere is an increasing possibility (Houghton et al. 1990). Currently the speed of the warming is high, 0.26 °C per decade during the past 15 years (Woodwell and Mackenzie 1995). The Intergovernmental Panel on Climate Change (IPCC) has concluded that a doubling of the atmospheric CO_2 concentration would likely change the mean global temperature by 1.5 to 4.5 °C after equilibrium conditions were reached (Houghton et al. 1990). Warming is projected to take only 50 to 100 years and would be concentrated more at high latitudes than low latitudes, more during winter than summer (Houghton et al. 1990). Woodwell and Mackenzie (1995) state that the earth's climate is not merely moving from one state of approximate equilibrium to another, but rather to a state of progressive instability.

Expected warming has been estimated to alter the distribution of vegetation over the globe, especially in the boreal and temperate zones (Emanuel et al. 1985, Leemans 1989, Smith et al. 1992, Monserud et al. 1993b). An increasing number of studies have used global vegetation models to analyze carbon (C) storage changes in the global biosphere under CO_2 doubling climate scenarios derived from general circulation models (GCM's) (Prentice and Fung 1990, Smith et al. 1992, Solomon et al. 1993, Smith and Shugart 1993, Cramer and Solomon 1993, Melillo et al. 1993, Dixon et al. 1994). More detailed process-based carbon dynamic models have been developed to assess both the influence of CO_2 concentration and climatic change on global and regional patterns of NPP (net primary productivity) (Janecek et al. 1989, Running and Nemani 1991, Smith et al. 1992, Mellilo et al. 1993).

Terrestrial vegetation may affect warming by means of feedbacks directly through the heat balance with changed albedo and indirectly through a mass transfer of carbon into the atmosphere (Janecek et al. 1989, Apps et al. 1993). Because boreal forests store a large amount of carbon (Kolchugina and Vinson 1993a) and are located in latitudes that are predicted to undergo the greatest warming, they may play a key role in future carbon fluxes (Dixon et al. 1994). Signs and magnitudes of resulting fluxes are still unclear, however. Neilson (1993) indicate that with warmer and drier climates boreal forests with high C stores will likely decrease in extent because of strong invasion by grasslands. Greater frequency and severity of forest fires predicted for boreal forests under global warming would release considerable carbon into the atmosphere (Perry et al. 1991). Smith et al. (1992) estimated enlarged C pools in boreal forests due to increased forest productivity and expansion into the current Tundra zone. A more accurate estimation of carbon gain or loss in vegetation under future warming could correct estimates of future CO_2 concentrations.

Our goal is to evaluate changes in phytomass of the vegetation of Siberia under projected CO_2-doubling climate change scenarios. Phytomass is total live plant mass (above- and belowground), including all forest stories and surface layers. Phytomass density is phytomass per unit area. Because we use climate change projections from different GCM's, we can assess phytomass sensitivity to different climate change scenarios. We couple a Siberian vegetation model (Tchebakova et al. 1994) with four CO_2-doubling climate change scenarios varying in global warming predictions. As with Solomon (1986), our strategy is to study regional climate change effects by coupling climate change scenarios from GCM's with a regional vegetation model. Regional vegetation models afford much greater accuracy and resolution than global vegetation models for the same region. We derive phytomass density estimates from the authoritative and comprehensive compilation of Bazilevich (1986, 1993), supplemented by additional literature on Siberian forests (see Methods section 2.3). We assume that all changes in phytomass are a result of the redistribution of vegetation zones. Because the Siberian vegetation model is an equilibrium model, we do not consider dynamic aspects of the carbon cycle, such as transient changes in vegetation redistribution (e.g., migration rate). We assume that the future forested percentage of a given vegetation class will remain unchanged from the present, which implicitly assumes a continuation of current rates of land use, fires, insect outbreaks, and other disturbances. Furthermore, we focus on phytomass, and do not attempt to evaluate possible effects of climate change on soils and the enormous amount of carbon stored in peatlands.

2 Methods

2.1 Climatic Data

We used an improved version of the IIASA Climate Database (Leemans and Cramer 1991) containing a global network of temperature, precipitation, and cloudiness. Vapor pressure was taken primarily from climatic reference books for the former USSR (Gidrometeoizdat 1964–1970). Data from about 1200 weather stations in Siberia were used to interpolate precipitation on a 0.5° grid, and about 800 to 900 stations were used to interpolate temperature, vapor pressure, and cloudiness. Albedo (necessary to calculate Budyko's dryness index) was taken from Matthews' (1983) digitized albedo estimates for the continents. This climatic data became input to the Siberian vegetation model, which predicted a vegetation class for each half-degree latitude by half-degree longitude grid cell.

Climate change scenarios are expressed in terms of temperature and precipitation using the procedures listed by Monserud and Leemans (1992). The differences between the current climate computer control run and the doubled CO_2 run are determined for a given general circulation model (GCM) of the atmosphere. These differences are interpolated from the coarser GCM grid to the finer 0.5° by 0.5° vegetation model grid using the same smooth surface fitting procedure of Leemans and Cramer (1991). This interpolation was done for all monthly temperature and precipitation values. The absolute value of the temperature differences and the ratio of the precipitation estimates are calculated for each grid cell on the finer grid. The doubled CO_2 climate database is created by adding the temperature differences to the current climate database and by multiplying precipitation by the precipitation ratio. The climate change scenario is then created by using the doubled CO_2 climate database as input to the Siberian vegetation model.

We used climate change projections corresponding to a doubling of CO_2 from the following four GCM's: GFDL, Geophysical Fluid Dynamics Laboratory of NOAA at Princeton (Wetherald and Manabe 1986, Manabe and Wetherald 1987); GISS, Goddard Institute for Space Studies of NASA at Columbia University (Hansen et al. 1983); OSU, Oregon State University at Corvallis (Schlesinger and Zhao 1989); and UKMO, United Kingdom Meteorological Office (Mitchell 1983, Wilson and Mitchell 1987). Based on predictions of vegetation change from two global vegetation models and the Siberian vegetation model used here, the GISS and OSU scenarios indicated more moderate warming than did the GFDL or UKMO scenarios, which predicted the greatest change (Monserud and Leemans 1992, Monserud et al. 1993a, 1993b).

We used the following boundaries to delineate

Siberia: the area between 60°E (Ural Mountains) in the west, 140°E (Tchersky Mountains) in the east, 50°N (Mongolian border) in the south, and 76°N (Arctic Ocean) in the north. Because the model was not designed for maritime climates, we excluded the southeast corner of this region (the vicinity of the Sea of Okhotsk): south of 60°N and east of 130°E. Note that this simplified region includes a portion of Kazakhstan in the southwestern corner, as well as a small area of northern Mongolia (between the Tuva and Buryat regions) and northeastern China (near the Amur River); these regions outside Siberia total 9 % of our study area.

2.2 The Siberian Vegetation Model

The Siberian vegetation model (Tchebakova et al. 1994) is based on bioclimatological considerations. It simulates the major vegetation classes (biome subdivisions) of Siberia from three climatic indices: growing degree-days (base 5 °C), dryness index, and continentality index. Because these indices reflect requirements of plants for warmth, drought resistance, and cold tolerance, they define the main features of vegetation zones (biomes) and their subdivisions. Climatic inputs (monthly mean temperature, precipitation, vapor pressure, cloudiness, and albedo) are obtained from a global climatic database, supplemented by additional weather stations in Siberia; resolution is 0.5° longitude by 0.5° latitude. Because this model is a static equilibrium model, it can only predict the types of vegetation that are suited to the climate of a locality, not the vegetation that will actually be there. Note that the Siberian vegetation model is not sensitive to the distribution of permafrost.

Growing Degree-Days (Tuhkanen 1980) and the closely related concept of Temperature Sums used in Russian literature (Tchebakova et al. 1994) are widely recognized as useful parameters for characterizing the heat requirements for plants. We chose Growing Degree Days above a base temperature of 5 °C (GDD_5), the minimum temperature required for plant growth in cold climates (Prentice et al. 1992).

Dryness Index characterizes the dryness of climates (Budyko 1974). It is the ratio of annual potential evaporation to precipitation. Potential evaporation is approximated as radiation balance divided by the latent heat of vaporization of water. This converts energy flux (radiation balance) to an equivalent evaporation. Radiation balance is determined according to the methodology of Budyko (1974), with improvements by Zubenok (1976) and Efimova (1977) (see Tchebakova et al. 1993 or Monserud et al. 1993b for details). Dryness Index (DI) is strongly related to a ratio of actual and equilibrium evapotranspiration used by Prentice et al. (1991) to characterize drought stress in plants.

Continentality Index (Conrad 1947) attempts to characterize the severity of climates on large continents. We characterize severe continental climates in Siberia as having low winter temperatures, short frost-free periods, limited moisture in spring, and the maintenance of permafrost in eastern and northern Siberia. Moving west to east, there are gradients of increasing continentality and decreasing humidity as moisture is removed from air masses.

Conrad's Continentality Index (CI) is a function of latitude (distance from the equator) and the difference in summer maximum and winter minimum temperatures. Nazimova et al. (1990) found continentality index of great importance for classifying vegetation in the Siberian subcontinent. Tchebakova et al. (1994) found that CI was strongly correlated ($r = 0.94$ for 116 stations in Siberia) to mean temperature of the coldest month (January for Siberia), which was used effectively by Prentice et al. (1992) in their global biome model.

These three indices classify Siberian vegetation in three dimensions. Dryness index classifies vegetation into broad biomes such as *Taiga* ($DI < 2$), *Steppe* ($2 \leq DI < 3.3$), and *Desert* ($DI \geq 3.3$); these are zonobiomes according to Walter (1983). Growing degree-days classify vegetation into mostly latitudinal thermic bands representing vegetation zones as *Tundra*, *Forest-Tundra*, the subdivisions of the Taiga biome (*Northern*, *Middle*, and *Southern Taiga*, and *Subtaiga*), and *Forest-Steppe*. Forest-Steppe is additionally separated as a drier class than Southern Taiga and Subtaiga by dryness index. Continentality index classifies vegetation into three longitudinally distinct sectors: the continental western sector, the more continental central sector, and the extremely continental eastern sector. Note that the moderate continental climate of European Russia (west of the Ural Mountains) is less continental than all these sectors of Siberia. The intersection of a zone and a sector determines a vegetation class. These latitudinal and longitudinal divisions are only approximate and may be interrupted by mountains.

Three temperate classes (Forest-Steppe, Steppe, and Semidesert) have been incorporated into the model although they do not occur under modern climates in Siberia. These temperate classes are predicted to become significant under global warming.

Tchebakova et al. (1994) examined the performance of the model by comparing predictions with the detailed Landscape Map of the USSR (Isachenko 1988), which was not used for model development. Isachenko's map is based primarily on vegetation and geomorphology, using a vegetation classification similar to that used by Tchebakova et al. (1994). Predicted vegetation generally matches well with mapped vegetation. The general locations of all vegetation zones are predicted correctly. Kappa statistics, which objectively measure cell-by-cell agreement between maps (Monserud and Leemans 1992), show good agreement at all scales of comparison (Tchebakova et al. 1994).

2.3 Phytomass Estimation

We rely on the Russian literature to obtain estimates of phytomass density. Our main sources are the major compilations by Bazilevich (1986, 1993) and Bazilevich et al. (1986), which we refer to simply as Bazilevich. These papers summarize phytomass results for the former USSR compiled from over 500 publications describing more than 2500 research plots. For our Siberian study area we used data from approximately 500 of these plots. Bazilevich used a zonal vegetation classification system – including sectors of continentality – very similar to the classification system used by Tchebakova et al. (1994). Therefore, our vegetation classes were easily identified in terms of the Bazilevich classification, although auxiliary information on dominant tree species was also used. For each vegetation class we calculate mean phytomass density (and standard deviation) from the plot data presented by Bazilevich (1986, 1993) and Bazilevich et al. (1986), with additional data from Pozdnyakov et al. (1969), Wielgolaski (1972), Mitrofanov (1977), Protopopov and Zyubina (1977), Semechkina (1978), Semechkin and Tetenkin (1980), Kuzmina and Spitsyna (1984), Stakanov (1984), Zyubina (1984), Falaleev (1985), Ermolenko (1987), and Alimov et al. (1989) (Table 1).

To estimate total phytomass density, above-ground phytomass was summed with root phytomass per unit area (Bazilevich 1986, 1993, Bazilevich et al. 1986). If roots were not measured, root phytomass was estimated to be 20 % of above-ground phytomass, based on results from Atkin (1984), Onuchin and Borisov (1984), and Ermolenko and Ermolenko (1982). Bazilevich (1993, p. 8) lists root phytomass in productive stands to be 17–20 % of above-ground phytomass, increasing to 25 % in less productive stands.

The studies of Semechkin and Tetenkin (1980), Zyubina (1984), Falaleev (1985), and Alimov et al. (1989) were designed to measure stem volume rather than phytomass for the stand. We calculated total phytomass density by multiplying stem volume per hectare by species-specific conversion coefficients (Isaev et al. 1993) relating stem volume to phytomass of leaves, woody above-ground and below-ground parts of plants, and general stage of stand development. Because understory vegetation was not measured in these stem volume studies, we assumed understory vegetation accounted for an additional 10 % of total phytomass density. This figure is intermediate between the 3–5 % found for Middle and Southern Taiga and the 20 % reported in open Northern Taiga (Alexeev and Birdsey 1994).

We make one modification to Bazilevich's estimates; her phytomass density values are for the Forest component only in forest ecosystems. We calculate a weighted average for total phytomass density using the observed forested and non-forested proportion in each vegetation class compiled by Alexeev and Birdsey (1994) from 1988 forest inventory data (Table 2).

Bazilevich does not give a measure of variation or precision for her phytomass density esti-

Table 1. Mean and standard deviation of phytomass density for Siberian vegetation classes. Data sources are listed under References.

No.	Vegetation class (and sector)	Mean density (t ha^{-1})	Standard deviation (t ha^{-1})	Reference
1	Tundra	17.9	10.0	Bazilevich 1986, 1993, Bazilevich et al. 1986, Wielgolaski 1972
2	Spruce-larch Forest-Tundra (Western Sector)	51.7	22.4	Bazilevich 1986, 1993, Bazilevich et al. 1986
3	Larch Forest-Tundra (*Larix sibirica, L. gmelinii*) (Central Sector)	49.6	16.5	Bazilevich et al. 1986, Bazilevich 1993
4	Larch Forest-Tundra (*L. cajanderii*) (Eastern Sector)	47.0	8.9	Bazilevich 1993
5	Dark-needled Northern Taiga (Western Sector)	123.5	-	Bazilevich et al. 1986
6	Light-needled Northern Taiga (Central Sector)	107.6	24.0	Bazilevich 1993, Pozdnyakov et al. 1969
7	Larch Northern Taiga (Eastern Sector)	57.8	14.9	Bazilevich et al. 1986, Bazilevich 1993, Pozdnyakov et al. 1969, Alimov et al. 1989
8	Dark-needled Middle Taiga (Western Sector)	207.5	35.5	Bazilevich 1986, 1993, Bazilevich et al. 1986, Mitrofanov 1977, Falaleev 1985
9	Light-needled Middle Taiga (Central Sector)	153.3	97.3	Bazilevich 1993, Bazilevich et al. 1986, Pozdnyakov et al. 1969, Mitrofanov 1977
10	Larch Middle Taiga (Eastern Sector)	138.6	43.4	Bazilevich 1986, 1993, Bazilevich et al. 1986, Pozdnyakov et al. 1969, Mitrofanov 1977
11	Dark-needled Southern Taiga (Western Sector)	229.2	51.7	Bazilevich 1986, 1993, Bazilevich et al. 1986
12	Light-needled Southern Taiga (Central Sector)	224.3	79.3	Bazilevich 1993, Bazilevich et al. 1986, Semechkin and Tetenkin 1980, Ermolenko 1987
13	Birch Subtaiga (Western Sector)	213.3	-	Bazilevich 1993, Bazilevich et al. 1986
14	Light-needled Subtaiga (Central Sector)	181.6	57.9	Bazilevich 1986, Protopopov and Zyubina 1977, Zyubina 1984
15	Birch Forest-Steppe (Western Sector)	156.8	68.7	Bazilevich 1986, 1993, Bazilevich et al. 1986
16	Light-needled Forest-Steppe (Central Sector)	179.6	38.6	Bazilevich 1986, 1993, Kuzmina and Spitsyna 1984, Zyubina 1984, Stakanov 1984, Semechkina 1978
17	Larch Forest-Steppe (Eastern Sector)	131.5	-	Pozdnyakov et al. 1969
18	Semiarid Steppe (Western Sector)	17.8	3.3	Bazilevich 1986, 1993, Bazilevich et al. 1986
19	Arid Steppe (Central Sector)	15.3	4.9	Bazilevich 1986, 1993, Bazilevich et al. 1986
20	Cryoarid Steppe (Eastern Sector)	10.9	1.8	Bazilevich 1986, 1993, Bazilevich et al. 1986
21	Temperate Forest-Steppe	163.6	-	Bazilevich 1986
22	Temperate Steppe	14.4	5.3	Bazilevich 1986, 1993, Bazilevich et al. 1986
23	Semidesert	8.2	1.5	Bazilevich 1986

Table 2. Total phytomass densities (t ha^{-1}) calculated for Siberian vegetation classes, assuming each class contains a specified non-forest component as well. Component class densities are multiplied by the forested and non-forested proportion to produce a mean density for the forest and non-forest components, respectively. Their sum is the total density for the vegetation class. Note that the non-forest component for all Taiga classes is "Meadows of the Boreal Zone" with an mean phytomass density of 13.8 t ha^{-1} (Bazilevich 1986, 1993).

Vegetation class (and sector)	Phytomass density by component (t ha^{-1})		Proportion		Total phytomass density (t ha^{-1})		
	Forested	Non-forested	Forested	Non-forested	Forested	Non-forested	Total
Tundra	0.0	17.9	0.00	1.00	0.0	17.9	17.9
Spruce-larch Forest-Tundra (Western)	51.7	17.9	0.25	0.75	12.9	13.4	26.3
Larch Forest-Tundra (Central)	49.6	17.9	0.30	0.70	14.9	12.5	27.4
Larch Forest-Tundra (Eastern)	47.0	17.9	0.25	0.75	11.7	13.4	25.2
Dark-needled Northern Taiga (Western)	123.5	13.8	0.40	0.60	49.4	8.3	57.7
Light-needled Northern Taiga (Central)	107.6	13.8	0.85	0.15	91.5	2.1	93.5
Larch Northern Taiga (Eastern)	57.8	13.8	0.35	0.65	20.2	9.0	29.2
Dark-needled Middle Taiga (Western)	207.5	13.8	0.40	0.60	83.0	8.3	91.3
Light-needled Middle Taiga (Central)	153.3	13.8	0.85	0.15	130.3	2.1	132.4
Larch Middle Taiga (Eastern)	138.6	13.8	0.75	0.25	103.9	3.5	107.4
Dark-needled Southern Taiga (Western)	229.2	13.8	0.35	0.65	80.2	9.0	89.2
Light-needled Southern Taiga (Central)	224.3	13.8	0.85	0.15	190.7	2.1	192.7
Birch Subtaiga (Western)	213.3	13.8	0.35	0.65	74.7	9.0	83.6
Light-needled Subtaiga (Central)	181.6	13.8	0.85	0.15	154.4	2.1	156.4
Birch Forest-Steppe (Western)	156.8	17.8	0.20	0.80	31.4	14.2	45.6
Light-needled Forest-Steppe (Central)	179.6	15.3	0.40	0.60	71.8	9.2	81.0
Larch Forest-Steppe (Eastern)	131.5	10.9	0.40	0.60	52.6	6.5	59.1
Semiarid Steppe (Western)	119.1	17.8	0.05	0.95	6.0	16.9	22.9
Arid Steppe (Central)	221.9	15.3	0.05	0.95	11.1	14.5	25.6
Cryoarid Steppe (Eastern)	119.1	10.9	0.05	0.95	6.0	10.3	16.3
Temperate Forest-Steppe	163.6	15.3	0.30	0.70	49.1	10.7	59.8
Temperate Steppe	194.3	14.4	0.05	0.95	9.7	13.7	23.4
Semidesert	0.0	8.2	0.00	1.00	0.0	8.2	8.2

mates. By compiling all individual plot phytomass density values from Bazilevich (1986, 1993), Bazilevich et al. (1986), and the other phytomass publications, we were able to estimate the standard deviation of the distribution of phytomass density for each vegetation class (Table 1); note that this value is not the standard error of the mean. These estimates of variation allowed us to calculate the precision of our final phytomass estimates for Siberia. The 95 % confidence interval was calculated using the standard formula of $\overline{X} \pm z \times S / \sqrt{n}$, with mean $\overline{X}$, z the standard normal deviate corresponding to $\alpha = 5$ %, S the standard deviation, and n the sample size. The standard deviation S of total phytomass was estimated by first calculating total phytomass using $\overline{X}_i + S_i$ and $\overline{X}_i - S_i$ from Table 1 and dividing the difference by 2, where $\overline{X}_i$ is mean phytomass density and S_i the standard deviation for vegetation class i.

Table 3 lists area estimates for each vegetation class based on the current climate and climate change projections. Simple multiplication of area by mean phytomass density gives total phytomass per vegetation class.

Table 3. Areas and predicted total phytomass of vegetation classes under present and climate warming.

Vegetation class (and sector)	Area (units = 10 000 km^2)					Phytomass (Pg)				
	Current climate	Climate change				Current climate	Climate change			
		GISS	OSU	GFDL	UKMO		GISS	OSU	GFDL	UKMO
Tundra	140.0	22.0	40.1	14.9	19.4	2.5	0.4	0.7	0.3	0.3
Spruce-larch Forest-Tundra (Western)	31.0	42.8	35.2	19.4	22.2	0.8	1.1	0.9	0.5	0.6
Larch Forest-Tundra (Central)	93.3	17.3	23.6	6.9	1.1	2.6	0.5	0.6	0.2	0.1
Larch Forest-Tundra (Eastern)	10.9	0.9	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0
Dark-needled Northern Taiga (Western)	64.6	77.8	45.1	41.9	54.3	3.7	4.5	2.6	2.4	3.1
Light-needled Northern Taiga (Central)	186.5	99.0	88.0	43.1	12.5	17.4	9.3	8.2	4.0	1.2
Larch Northern Taiga (Eastern)	19.8	4.3	7.8	1.1	0.0	0.6	0.1	0.2	0.0	0.0
Dark-needled Middle Taiga (Western)	53.5	50.2	35.0	26.4	41.2	4.9	4.6	3.2	2.4	3.8
Light-needled Middle Taiga (Central)	105.9	85.0	101.6	48.6	24.5	14.0	11.3	13.4	6.4	3.2
Larch Middle Taiga (Eastern)	29.8	1.3	7.2	0.1	1.2	3.2	0.1	0.8	0.0	0.1
Dark-needled Southern Taiga (Western)	52.2	36.7	25.0	16.6	21.1	4.7	3.3	2.2	1.5	1.9
Light-needled Southern Taiga (Central)	37.7	65.4	85.4	43.8	41.1	7.3	12.6	16.5	8.4	7.9
Birch Subtaiga (Western)	53.2	99.4	61.2	39.7	70.4	4.4	8.3	5.1	3.3	5.9
Light-needled Subtaiga (Central)	15.2	122.7	134.9	73.2	110.6	2.4	19.2	21.1	11.5	17.3
Birch Forest-Steppe (Western)	50.0	41.2	31.6	30.7	15.2	2.3	1.9	1.4	1.4	0.7
Light-needled Forest-Steppe (Central)	13.7	34.2	53.9	79.3	54.8	1.1	2.8	4.4	6.4	4.4
Larch Forest-Steppe (Eastern)	5.5	21.6	47.5	30.1	1.3	0.3	1.3	2.8	1.8	0.1
Semiarid Steppe (Western)	28.1	0.5	0.2	2.6	0.2	0.6	0.0	0.0	0.1	0.0
Arid Steppe (Central)	7.2	2.0	3.9	3.2	0.0	0.2	0.1	0.1	0.1	0.0
Cryoarid Steppe (Eastern)	7.5	0.8	2.0	6.4	0.4	0.1	0.0	0.0	0.1	0.0
Temperate Forest-Steppe	0.2	138.7	119.0	379.3	444.4	0.0	8.3	7.1	22.7	26.6
Temperate Steppe	23.2	76.3	83.1	132.7	101.3	0.5	1.8	1.9	3.1	2.4
Semidesert	12.3	1.0	9.9	1.2	4.1	0.1	0.0	0.1	0.0	0.0
Total	1041.1	1041.1	1041.1	1041.1	1041.1	74.1	91.3	93.6	76.6	79.6

3 Results

3.1 Phytomass

Under current climate, we estimate the total phytomass of Siberia to be 74.1 ± 2.0 Pg (Petagram = 10^{15} g). Note that this estimate is based on the observed forested proportion in each vegetation class compiled by Alexeev and Birdsey (1994) from current forest inventory data (Table 2). Phytomass estimates for climate change (CO_2-doubling) scenarios fell into two groups (Table 3). Moderate warming associated with the GISS and OSU projections resulted in a 23–26 % increase in phytomass (to 91.3 ± 2.1 Pg and 93.6 ± 2.4 Pg, respectively). Extreme warming associated with the GFDL and UKMO projections resulted in a small 3–7 % increase in phytomass (to 76.6 ± 1.3 Pg and 79.6 ± 1.2 Pg, respectively). In all four climate change scenarios, the phytomass stock of all colder, northern classes is predicted to be reduced considerably (viz., Tundra, Forest-Tundra, Northern Taiga, and Middle Taiga). In the moderate OSU-GISS warming this reduction was 40 %, from 50 Pg to 30 Pg. The reduction with the extreme UKMO-GFDL scenarios was 70–75 %, down to approximately 15 Pg. Phytomass increases 30–50 % in Southern Taiga with the OSU-GISS scenarios, and decreases 15 % with the UKMO-GFDL scenarios. Phytomass in Subtaiga increases greatly with all scenarios, from a doubling with GFDL to quadrupling with OSU and GISS. Overall, phytomass of the Taiga biome (Northern, Middle, Southern, and Subtaiga) increased 15 % in the moderate OSU and GISS scenarios and decreased by a third in the UKMO and GFDL projections. The phytomass of Forest-Steppe doubles with all GCM's.

The most important change found in all scenarios is the introduction of a vast Temperate Forest-Steppe zone, predicted to cover up to 40 % of the area of Siberia (UKMO-GFDL); with current climate, this vegetation class is nearly non-existent. Temperate Forest-Steppe phytomass is three times larger in the warmer UKMO-GFDL scenarios (23–27 Pg) than in the moderate OSU-GISS scenarios (7–8 Pg). The area of the Temperate Steppe zone also increases greatly (3–5 times in all scenarios), but the low mean phytomass values of Steppe means that this expansion will not be accompanied by an important increase in phytomass.

In Figs. 1–3, we calculate the geographic distribution of phytomass density by 40 t/ha classes for current climate as well as both moderate (GISS) and extreme (GFDL) warming. Under current climate (Fig. 1), the most productive ecosystems with density > 120 t/ha are found in the southeast quarter of Siberia, mostly below 60°N latitude and east of 90°E longitude. Under the moderate warming in the GISS scenario (Fig. 2), the area of high phytomass density significantly expands and spreads northeast, as far as 70°N latitude. Under the extreme warming of the GFDL scenario (Fig. 3), these high density areas would noticeably shift northwards and somewhat increase in size. The highest density class (light-needled Southern Taiga) shifts so far north that it is centered at 67°N latitude, in the heart of Yakutia. In the GFDL scenario, smaller high density regions also remain in southern Siberia in the Sayan Mountains and the tablelands northeast of Lake Baikal. Medium density (80–120 t/ha) vegetation classes both shrink in size and shift to the north as simulated warming increases from current climate to moderate (GISS) and extreme (GFDL) warming (Figs. 1–3).

Under both the GISS and GFDL warming scenarios, the area of low density ecosystems (Tundra and Forest-Tundra, all less than 40 t/ha) in the north shrinks dramatically. In the south, the location and area of the low phytomass density ecosystems (primarily Steppe) do not change much.

The most striking features of the phytomass predictions from an increasingly warm climate in Figs. 1–3 are both the dramatic northeastern shift in the high phytomass density classes (light-needled Middle Taiga, Southern Taiga, and Subtaiga), and the enormous expansion of the intermediate density class (40–80 t/ha) dominated by Temperate Forest-Steppe.

We also estimated phytomass assuming potential vegetation is possible. We replaced the observed forested percentages from Alexeev and Birdsey (1994) with potential values by Permiakov (1974). Potential forested percentage increased to 55 % for Forest-Tundra, 85 % for all Taiga classes, and 60 % for Forest-Steppe. As a result, current potential phytomass increased to 98.1 ± 2.4 Pg, a substantial increase (24 Pg) over

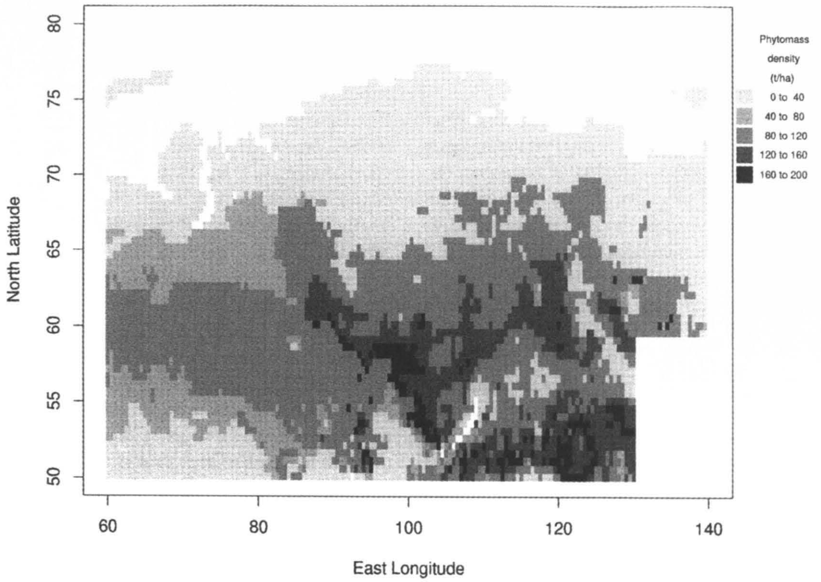

Fig. 1. Predicted Siberian phytomass distribution under current climate.

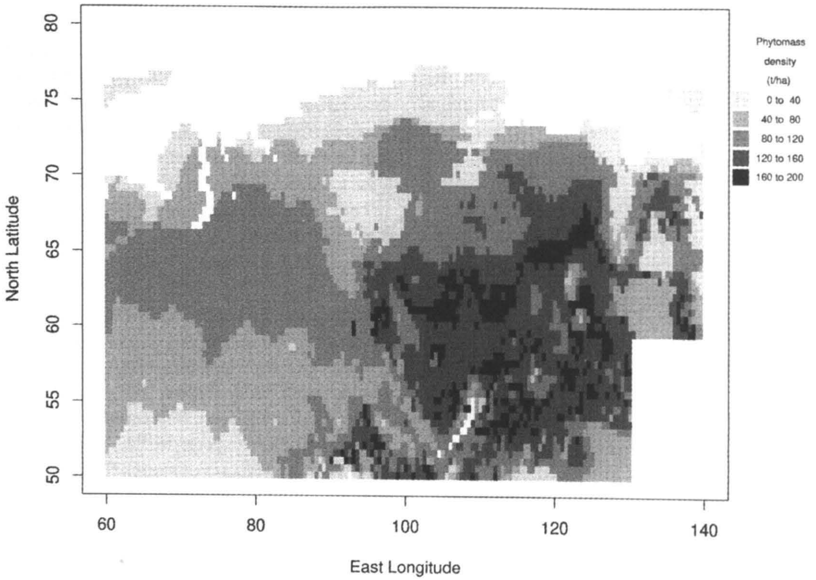

Fig. 2. Predicted Siberian phytomass distribution under the moderate warming of the GISS climate change scenario.

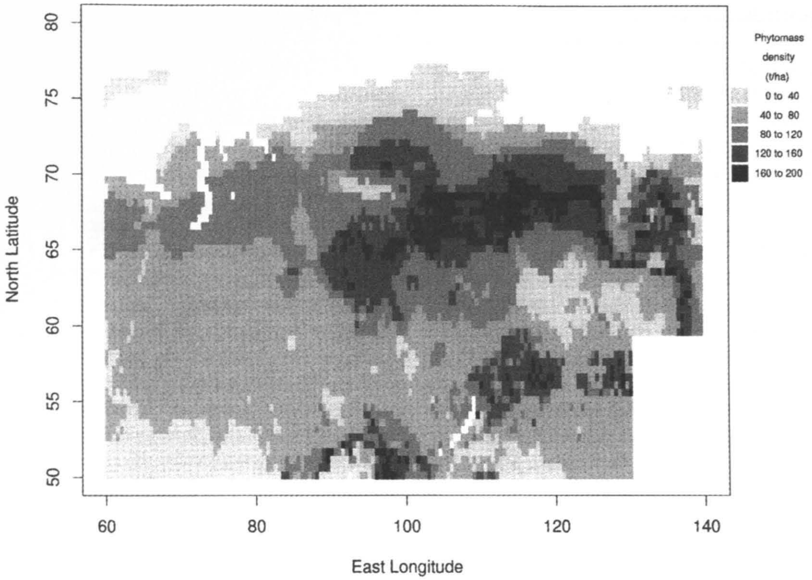

Fig. 3. Predicted Siberian phytomass distribution under the extreme warming of the GFDL climate change scenario.

actual current phytomass. Most of this difference results from an increase in the forested percentage in the Taiga biome. Estimates of potential phytomass from climate change scenarios increased 25–38 Pg (25–50 %) over estimates using the observed forested percentage. The major difference was in the Temperate Forest-Steppe class, and was a result of increasing the forested percentage from 30 % to 60 %.

4 Discussion

Results indicate enormous potential change in the spatial distribution of vegetation in Siberia due to climate change (CO_2-doubling). Although the GFDL and UKMO scenarios predict more extreme warming than the GISS and OSU scenarios, all four GCM's predict large reductions in the area of Tundra and Forest-Tundra, reductions and northern shifts in the various classes of Taiga, and reductions in Steppe. Large increases in area are predicted for the Temperate Forest-Steppe and Temperate Steppe vegetation zones, and for Forest-Steppe and Subtaiga in the Boreal zone. Generally, vegetation bands are predicted to shift northward and somewhat east, with extensive areas of temperate vegetation introduced in the south. Steppe and Tundra will shift eastward. Tundra and Northern Taiga are predicted to move 600–1000 km north, while Middle and Southern Taiga are predicted to move 1000–1500 km north (Monserud et al. 1993a). Subboreal Steppe and Temperate Forest-Steppe will invade north as far as 2500 km. Under the somewhat more moderate changes predicted by the GISS and OSU scenarios, distances that vegetation classes shift will be about 1.5 times less than with the GFDL and UKMO scenarios, although the direction of shift (northeasterly) is about the same. Temperate Forest-Steppe is predicted to penetrate into the current boreal zone as much as 3000 km. Kappa statistics (Monserud and Leemans 1992) for judging agreement between the current climate vegetation map and the climate change predictions indicate essentially no agreement between maps, thus confirming the visual impression of wholesale change in the predicted vegetation of Siberia (Monserud et al. 1993a).

The resulting effect on total phytomass depends on the degree of warming. With moderate warming (OSU and GISS), phytomass is predicted to increase by 25 %. With greater warming (UKMO and GFDL), the predicted increase in phytomass is small, 3–7 %. These conflicting results can largely be explained by the effect of warming on the future distribution of Taiga. Southern Taiga and especially Subtaiga will flourish under the moderate warming scenarios. In contrast, Taiga will shrink while Forest-Steppe and Steppe expand with the more extreme warming scenarios. Because Forest-Steppe and Steppe have considerably less mean phytomass than Taiga, a decrease in total phytomass then occurs. Thus, for phytomass estimation, it matters greatly which GCM is being used to predict climate change.

The question of precision is difficult, for the accuracy of the maps is not stated, and no measure of precision or variation is listed in Bazilevich (1986,1993) or the other phytomass publications. We overcame this latter shortcoming by estimating the variance (by vegetation class) of all the individual plot phytomass density values that we could find in the available literature, primarily Bazilevich (1993). This allowed us to estimate the precision of the final phytomass estimate for current climate as 74.1 ± 2.0 Pg, the 95 % confidence interval based on S = 23 Pg and sample size n = 520. Note that these estimates assume equilibrium conditions with the same rate of mortality due to forest fires, insects, and diseases. Although all three rates could increase under global warming, we have not attempted to adjust for such changes.

Permafrost is an important component of the Siberian landscape. Essentially all of eastern Siberia is in the permafrost zone, and most of that is continuous permafrost (Kolchugina and Vinson 1993b). Based on paleoanalogues from warm epochs like the mid-Holocene and the Last Interglacial climatic optima, the permafrost zone is predicted to retreat far north in Siberia under global warming (Velichko et al. 1995). Because eastern Siberia is already quite dry, it has the greatest potential for vegetation change with global warming. If eastern Siberia remains relatively dry under global warming, two divergent outcomes are possible. If drainage is poor, the buildup of extensive mire formations could begin. If drainage is good, current permafrost forest sites could become considerably drier, so dry that in such locations in Yakutia the *Larix* forests could be replaced by xerophytic shrubs and grasses (Tchebakova et al. 1995). In either case, above-ground phytomass storage would decrease. However, if precipitation is sufficient under warming, Siberian spruce (*Picea obovata* Ledeb.) could replace Siberian larch (*Larix sibirica* Ledeb.) in Northern Taiga; Siberian cedar (*Pinus sibirica* Du Tour) and Siberian fir (*Abies sibirica* Ledeb.) could replace Siberian larch in Middle Taiga, and Scots pine (*Pinus sylvestris* L.) and birch (*Betula pendula* Roth) could replace *Larix gmelinii* (Rupr.) Litv. and *L. dahurica* Turcz. in the extremely continental climatic zone in Yakutia (Velichko et al. 1995). Replacing *Larix* species with the more productive Taiga species from the west will increase phytomass production in eastern Siberia.

We wish to compare our Siberian phytomass estimate to available estimates for Russia (Isaev et al. 1993, Alexeev and Birdsey 1994) or the former USSR (Kolchugina and Vinson 1993a); we proportionally adjust their estimates by area for Siberia. All three studies calculated phytomass of forest land by broad age classes; in addition, all three excluded the Tundra biome. By relying primarily on the phytomass density data of Bazilevich (1986, 1993), we implicitly assume that all forests are mature rather than young growth. Of course, this is not true, for harvesting and fires result in new stand formation. Both Isaev et al. (1993) and Kolchugina and Vinson (1993a) present data on the areal distribution of young growth vs. mature stands in Russia and the former USSR, respectively, with the result that approximately 10 % of the area is young growth. This 10 % is surely too high for Siberia, where forest access for harvesting is considerably reduced over European Russia (Alexeev and Birdsey 1994), especially in the north and on permafrost. Thus, we estimate very conservatively that 10 % of the forested area in Siberia is in young growth stands. We estimate the phytomass of these young stands to be 4.5 % of mature stand phytomass, based on volume data by age class for administrative units in Siberia presented by Alexeev and Birdsey (1994). Reducing our phytomass estimate of 71.6 Pg (Tundra excluded) by 10 % for the area of young growth stands, and adding in the small contribution of phytomass from these young stands yields an estimate of 64.8 Pg for Siberia.

The studies of Isaev et al. (1993), Kolchugina and Vinson (1993a), Alexeev and Birdsey (1994), and Olson et al. (1983) are based on carbon, whereas ours is based on phytomass. For comparison purposes, we multiplied their estimates of total plant carbon by the constant 2, a conversion factor assuming phytomass is 50 % carbon (Isaev et al. 1993, Alexeev and Birdsey 1994).

We compared our estimates of current Siberian phytomass to those of Isaev et al. (1993), who examined Russia's forest ecosystems using the 1988 USSR Forest Inventory. Isaev et al. (1993) used phytomass density data from Bazilevich to calibrate the relationship between stand volume and phytomass. Because Isaev excluded the Tundra biome, we calculated the non-Tundra proportion of our Siberian study area to that of Isaev's to be 0.76. Multiplying by their total phytomass of 82.4 Pg yields 62.6 Pg. This is very close to our estimate of 64.8 Pg.

Kolchugina and Vinson (1993a) examined carbon pools in forest biomes in the former USSR, relying heavily on the work of Bazilevich (1986). Additional information on the proportion of young to mature stands was obtained from the USSR Forest Inventory. Kolchugina and Vinson (1993a) then reduced Bazilevich's mean phytomass densities for the proportion in young growth. Excluding both the Tundra and Steppe biomes, they estimated that the Taiga biome contained 100.8 Pg of phytomass over an area of 1306.2 × 10^4 km^2. The proportion of the area of the Taiga biome in our Siberian study area (822.7 × 10^4 km^2) is 0.63, which reduces their estimate to 63.5 Pg of phytomass for Siberia. This compares almost exactly to our estimate of 63.6 Pg, after excluding both Tundra and Steppe.

Alexeev and Birdsey (1994) give the lowest estimates of phytomass for Russia. They base their phytomass estimates of forest ecosystems on the same 1988 USSR Forest Inventory used by Isaev et al. (1993). Excluding the Tundra biome, Alexeev and Birdsey (1994) estimate phytomass for 723.9 × 10^4 km^2 of administrative units within our Siberian study area to be 32.9 Pg. This area is 80 % of our study area, which results in an estimate of 51.8 Pg of phytomass from our predictions. Thus, their estimate is 36 % less than ours for the same area. Because we use the same forested proportion (Table 2) as Alexeev and Birdsey (1994), one cause for such a large difference must be different estimates of phytomass density for the individual vegetation classes. For example, Alexeev and Birdsey (1994, Table 6.4) list the phytomass density of Middle Taiga in central and eastern Siberia as 90 and 58 t/ha, respectively, while we estimate the same densities from Bazilevich's data as 132 and 107 t/ha, respectively (Table 2).

Olson et al. (1983) provide plant carbon estimates for potential vegetation for the major biomes of the world. Under current climate, we compared our potential estimates for Siberia (using Permiakov's (1974) forested percentages) to Olson's global estimates for the Tundra, Taiga, and Steppe biomes as follows. First, we combined Northern, Middle, and Southern Taiga and Subtaiga into one Taiga class. Next, we calculated the proportion of the area in Siberia to Olson's global area for each of the three biomes. The resulting values compared to ours show very reasonable phytomass estimates: for Tundra our estimate is 2.5 Pg versus 2.3 Pg for Olson; for Taiga we estimate 93.9 Pg versus 90.7 Pg for Olson, and for Steppe we estimate 1.5 Pg versus 1.3 Pg for Olson. We conclude that our phytomass estimates are quite consistent with those of Olson et al. (1983), as well as those of Isaev et al. (1993), and Kolchugina and Vinson (1993a).

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