Agroclimatic potential across central Siberia in an altered twenty-first century

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Abstract
Humans have traditionally cultivated steppe and forest-steppe on fertile soils for agriculture. Forests are predicted to shift northwards in a warmer climate and are likely to be replaced by forest-steppe and steppe ecosystems. We analyzed potential climate change impacts on agriculture in south-central Siberia believing that agriculture in traditionally cold Siberia may benefit from warming. Simple models determining crop range and regression models determining crop yields were constructed and applied to climate change scenarios for various time frames: pre-1960, 1960–90 and 1990–2010 using historic data and data taken from 2020 and 2080 HadCM3 B1 and A2 scenarios. From 50 to 85% of central Siberia is predicted to be climatically suitable for agriculture by the end of the century, and only soil potential would limit crop advance and expansion to the north. Crop production could increase twofold. Future Siberian climatic resources could provide the potential for a great variety of crops to grow that previously did not exist on these lands. Traditional Siberian crops could gradually shift as far as 500 km northwards (about 50–70 km/decade) within suitable soil conditions, and new crops nonexistent today may be introduced in the dry south that would necessitate irrigation. Agriculture in central Siberia would likely benefit from climate warming. Adaptation measures would sustain and promote food security in a warmer Siberia.

Keywords: climate warming, central Siberia, agriculture, crop range and production

1. Introduction

World concerns about food security are growing as a result of observed and projected climate change impacts on agriculture. The scientific community agrees that climate change consequences differ for agriculture depending on geography; northern countries may benefit from global warming (Russia, northern China) and, in the absence of adaptation measures, southern countries and continents (Africa, Australia) may find their food security at risk due to climate warming. Despite a great degree of uncertainty, agriculture everywhere in Africa runs some risk of being negatively affected by climate change (Mueller et al. 2011). In the tropics, subtropics and temperate regions, without sufficient investment in adaptation, short-term events, like extreme seasonal temperatures, could become long-term trends and damage food crops and accepted agricultural practices (Battisti and Naylor 2009). Australian agriculture faces serious challenges of high rates of change in regional and local climates and abrupt, unexpected shifts in climate patterns with which farmers are not familiar and therefore do not have established coping mechanisms (Steffen et al. 2011).
In Europe, it is predicted that wheat (a reference crop) productivity will increase from 25 to 163% for the time period 2000–80, depending on the time and scenario (Ewert et al 2005). In northern China, generally, projected climate change could bring some potentially improved conditions for Chinese agriculture; however, these improved conditions would be challenged by unfavorable changes in water resources, and thus the overall agricultural outcome would be affected (Tao et al 2011). European Russia may not necessarily benefit from climate warming because the potential yield in the central and northern-forested regions would not compensate for a sharp drop in yields due to the increased frequency of droughts in the currently most productive southern regions (Dronin and Kirilenko 2010). Extreme weather events (high temperature, droughts, fires, etc) such as those in European Russia in the unprecedented hot and dry summer of 2010 are predicted to occur more often (Meshcherskaya et al 2011, Dronin and Kirilenko 2010, Wright et al 2009, Groisman et al 2007), especially in southern European Russia. However, the agriculture of the northern territories of Eurasia may benefit from climate change. Izrael and Sirotenko (2003) pointed out that the climate change impacts on agriculture in Russia as a whole are positive when weighing the positive and negative consequences. However, some regions may suffer crop reduction in the short-term due to abnormally dry summers. In European Russia, Sirotenko et al (2007) found that climate-based agri-production increased by 30% from 1980 to 1999 compared to the average 20-year production yields in the middle of the 20th century. They concluded that the bioclimatic potential (dry biomass of hay accumulated for the growing season, base 5°C), predicted with a dynamic simulation model, would increase over all of Russia depending on the natural moisture available from rain or provided by irrigation, soil fertility and CO₂ concentration. Climate change over the last three decades, 1975–2005, favored agriculture in 70% of Russia’s federal subjects (administrative units), producing 85% of its trade grain. However, during this same time period, West Siberia and East Siberia experienced crop decreases due to climate drying across arable lands (Sirotenko et al 2007).

Arable lands have been historically developed by humans in steppe and transitional forest-steppe zones, which have deep, fertile, chernozem soils (figure 1). In southern Siberia, food crops and also forage inhabit steppe and forest-steppe zones on analogous soils called Siberian chernozems (Dokuchaev 1882). Siberian crops are resistant to frequent droughts and the cold climate. In the 18th and 19th centuries, as arable lands became exhausted, Siberian farmers burned portions of the southern dark taiga that had been invaded and killed by massive infestations of the Siberian moth (Dendrolimus sibiricus) in order to expand arable land (Baranchikov and Kondakov 2002). During the 20th century, land use for agriculture grew in Siberia and reached its maximum in 1960–80. Cultivation of virgin and fallow lands was associated with growing industry and urbanization. In the forest-steppe and steppe ecozones of the Minusinsk basin located in southern Krasnoyarsky Kray and the adjacent Republic of Khakassia (hereafter Khakassia) (figure 1), 800 000 hectares (ha) of arable lands were established, although half of the lands were on saline and shallow soils of low fertility. These lands were heavily used with no soil-protective measures, which led to soil degradation, salinization, wind and water erosion. Arable lands were especially subject to degradation. In southern central Siberia, 1.5 million (mln) ha of arable lands were degraded. In Khakassia, in particular, 81% of the arable land was subject to aeolian erosion (Lysanova 2001). Degraded arable lands were taken out of the agriculture turnover cycle. Crop yields dropped sharply. Since 1991, a systematic crisis in agriculture has led to a further significant decrease in the amount of agricultural land, thus adversely affecting crop, livestock, and agricultural production and consumption. Thus, what began in the years of ‘perestroika’ as an unstable situation on Siberia’s agricultural lands has continued to the present. In south-central Siberia, 1 mln ha of agricultural land was temporarily taken out of production, and now there are efforts to use the land again.

In Khakassia, only one third of the arable land is in use; in southern Krasnoyarsk Kray, two thirds remain; and in the Republic of Tyva (hereafter Tyva), only half remains (Lysanova and Artemiuk 2006). Abandoned and fallow lands have...
begun a natural restoration process to become natural pasture lands. Although agricultural lands and livestock have been degraded and the associated shortage in agriculture production has negative socio-economic impacts, the ecological status of restoring agri-landscapes has significantly improved. During the last 2–3 years, some trends towards agricultural recovery have been noted due to both the efforts of the Ministry of Agriculture and possibly favorable climate conditions.

Previous model projections of climate impacts on Siberian vegetation have shown that both forest and non-forest biomes would shift northwards across Siberia by the end of the century based on HadCM3 climate change projections (Soja et al. 2007, Tchebakova et al. 2009, 2010). At the expense of forests, up to 50% of Siberia was predicted to be covered by forest-steppe and steppe that could be potentially suitable for agriculture if the soils were also suitable. In central Siberia (administrative divisions: Krasnoyarsk Kray and adjacent southern Khakassia and Tyva, figure 1), historic record-based climate averages were found to be 1–2°C warmer in both the summer and winter in the first decade of the 21st century, compared to the baseline of 1960–90. The change in precipitation was more complicated, increasing regionally on average by 10% but decreasing by 10–20% in the south, promoting further local drying in already dry landscapes (Tchebakova et al. 2011b). Forests were predicted to shift northwards, and steppe advancement was predicted as far as 56°N latitude into areas where steppe was previously nonexistent. Additionally, steppe expansion was predicted in the dry environments of Khakassia and Tyva. Simulated Hadley 2020 B1 and A2 climates and 2010 temperature and precipitation trends appeared to be similar to historic trends, in terms of both patterns and location (Tchebakova et al. 2011b), and may be reliably applied to studies of climate change impacts on agriculture.

Our goals are: (1) to evaluate ongoing climate change trends since 1960 and relate these to various crop distributions and yields; (2) to predict ‘hot spots’ of potential agricultural change in the pre-2010 climate and in the future using Hadley 2020 and 2080 climate change scenarios; (3) to develop new agroclimatic zonation (agricultural region) maps; and (4) finally, to model future crop potential that may evolve as the climate changes.

2. Data and methods

The study area is bounded by three federal subjects: the territory of Krasnoyarsky Kray, the adjacent Republic of Khakassia, and the Republic of Tyva at the southern border of Russia (figure 1). Records from 90 weather stations across this area are employed to evaluate changes in January and July temperatures and annual precipitation from 1991 to 2010 relative to the baseline climate of 1961–90. Data from 21 weather stations from the years 1961–2010 in three southern vegetation zones (forest-steppe, steppe and dry steppe) are used to evaluate climate change trends and climatic indices: growing degree days (GDD) > 5°C; and an annual moisture index (a ratio between GDD > 5°C and annual precipitation). All data are derived from Reference Books on Climate (1967–1971, 1960–2010), Reference Book for an Agronomist (Sinyagin and Tyutyunnikova 1978) and climate maps (Shotsky 1977, Lebedev and Populiakh 2005).

The baseline climate is used to calculate climatic differences for the near future, 1991–2020, and far future, 1991–2080. Climate change departures for these periods are derived from two climate change scenarios, the HadCM3 A2 and B1 of the Hadley Centre in the UK. The HadCM3 global climate model (GCM) is one of 23 respected climate models (Randall et al. 2007), and we have historically worked with this model, so for consistency we chose to use the HadCM3 model output; the greater climatic model differences occur between scenarios. These two scenarios, A2 and B1, represent, correspondingly, the highest and the lowest temperature increase by the end of the 21st century. The A2 scenario describes a continuously increasing population with regionally oriented economic development that is slower than other storylines, and the B1 scenario’s emphasis is on global solutions to economic, social and environmental sustainability (IPCC 2007, p 18).

Across the study area, the temperature projections for the two scenarios do not significantly differ in 2020. However, they differ significantly by 2080: the range of January temperature change is 2–6°C and 3–9°C for the B1 and A2 scenarios, respectively; July temperature changes are 1.5–4.5°C and 4.5–8°C for the B1 and A2 scenarios, respectively. Percentages of precipitation change are 0–10% by 2020 and 10–20% by 2080 in both scenarios (Tchebakova et al. 2011a). Because the predicted temperature increase is relatively larger than the precipitation increase by 2080, future climates are predicted to be much dryer, and moisture would be a limiting factor for forest vegetation distribution across Siberia. The Siberian BioClimatic Model (SiBChM) simulations predicted that the steppe would expand by 10–20% of the total study area, and the semidesert ecosystem would expand by 6.5–10% of the total area (Tchebakov and Parfenova 2011).

We use a local classification of agri-climatic regions that is developed to identify agri-regions across our study area: the Krasnoyarsky Kray, Khakassia and Tyva (Ivanov 1994, table 1). An ‘agri-region’ is a region with homogeneous climate, characterized by 150°C of GDD and a 1.25 annual moisture index (AMI) in this classification. The study area is stratified into 14 classes of GDD and four classes of AMI on a regular scale by both qualitative and quantitative properties. Additionally, we extended the present classification of the agri-regions with five new warmth classes using a regular scale of 200°C for a class (from ‘warm’ to ‘extremely hot’ marked by italic in table 1). Crop statistics for Krasnoyarsky Kray, Khakassia and Tyva are derived from Reference Books (1966a–2009, 1966b–2009, 1986–2009) correspondingly.

We constructed simple agri-climatic models that predict the geographic range and yields of annual agri-crops from two summer climatic indices: GDD, base 5°C, which represents temperature requirements for plant growth and development, and AMI, which characterizes resistance to moisture stress. Moisture conditions are usually characterized by a proportion between components of a water budget: precipitation and evapotranspiration. Precipitation is measured and evapotranspiration is a function of the radiation budget...
**Table 1.** Area change (%) in current and potential agri-regions in a warmer climate for time periods from 1960 to 2080. Agri-regions classified by warmth (growing degree days, GDD > 5 °C) and moisture (annual moisture index, AMI) across Krasnoyarsky Kray, Khakassia and Tyva (Ivanov 1994). Note that italic marks new agri-regions nonexistent in the current climate, and bold marks climatic conditions suitable for regular farming.

| Agri-regions by warmth | Before 1960 | 1961–1990 | 1991–2010 | B1 2020 | A2 2020 | B1 2080 | A2 2080 |
|------------------------|-------------|------------|------------|----------|----------|----------|----------|
| (1) Severe             | <50         | 4.7        | 3.3        | 2.4      | 1.8      | 0.3      | 0.0      |
| (2) Very cold          | 50–450      | 22.9       | 23.1       | 20.8     | 18.8     | 17.3     | 16.9     |
| (3) Cold               | 450–600     | 10.1       | 12.2       | 10.6     | 9.8      | 11.5     | 8.2      |
| (4) Moderately cold    | 600–900     | 26.5       | 25.1       | 22.0     | 18.5     | 21.4     | 18.4     |
| (5) Very cool          | 900–1050    | 14.0       | 14.2       | 14.1     | 11.8     | 14.1     | 7.9      |
| (6) Cool               | 1050–200    | 14.7       | 16.3       | 12.7     | 13.1     | 12.1     | 9.1      |
| (7) Moderately cool    | 1200–350    | 6.9        | 5.7        | 14.0     | 12.4     | 14.0     | 12.1     |
| (8) Insufficiently warm| 1350–500    | 0.3        | 0.2        | 3.3      | 12.3     | 7.3      | 10.3     |
| (9) Moderately warm    | 1500–650    | 0.1        | 0.8        | 0.6      | 10.0     | 11.6     |          |
| (10) Warm              | 1650–800    |            |            |          |          |          |          |
| (11) Very warm         | 1800–2000   |            |            |          |          |          |          |
| (12) Hot               | 2000–200    |            |            |          |          |          |          |
| (13) Very hot          | 2200–400    |            |            |          |          |          |          |
| (14) Extremely hot     | >2400       |            |            |          |          |          |          |

| Agri-regions by moisture | Before 1960 | 1961–1990 | 1991–2010 | B1 2020 | A2 2020 | B1 2080 | A2 2080 |
|--------------------------|-------------|------------|------------|----------|----------|----------|----------|
| (1) Surplus moisture     | <1.5        | 62.0       | 60.0       | 60.0     | 53.7     | 66.9     | 40.6     |
| (2) Sufficient moisture  | 1.5–2.75    | 34.2       | 35.3       | 34.3     | 37.7     | 31.0     | 41.8     |
| (3) Insufficient moisture| 2.75–4.0    | 3.1        | 4.0        | 4.7      | 7.3      | 1.5      | 15.4     |
| (4) Dry                  | >4.0        | 0.7        | 0.8        | 1.0      | 1.3      | 0.6      | 2.3      |

| Agri-regions by combination of warmth/moisture | Before 1960 | 1961–1990 | 1991–2010 | B1 2020 | A2 2020 | B1 2080 | A2 2080 |
|-----------------------------------------------|-------------|------------|------------|----------|----------|----------|----------|
| (1) Cold                                      | <900        | 64.1       | 63.6       | 55.8     | 49.4     | 52.0     | 33.7     |
| (2) Optimal                                   | >900/-4.0   | 35.2       | 35.6       | 43.2     | 49.3     | 47.4     | 64.0     |
| (3) Dry                                       | >4.0        | 0.7        | 0.8        | 1.0      | 1.3      | 0.6      | 2.3      |

| Crop                              | GDD (°C) |
|-----------------------------------|----------|
| Barley (early ripe), peas (early ripe) | >900    |
| Oatmeal (early ripe), barley (medium ripe) | >1050   |
| Spring wheat, winter wheat, maize (silage), oatmeal | >1200  |
| Sunflower (seeds), Spring wheat (late ripe) | >1500   |
| Maize (grain), sugar beets, beans, millet | >1650   |
| Rice, soya beans, grapes*         | >1800   |
| Apricots*                         | >2000   |

and is approximated by GDD in various moisture indices (Budyko 1974). The GDD ranges (table 2) were derived from agroclimatology (Sinitsyna et al 1973, Gumieniuk et al 2010). AMI was assumed not to be a limiting factor for agri-crops under the value of AMI < 6, which is a lower border of zonal semidesert (Sinitsyna et al 1973).

Bioclimatic crop yield models were constructed as multiple linear regressions relating crop yields to GDD and an annual moisture index. Crop data were presented by 30 farming regions located in unique climates in forest-steppe, steppe and dry steppe zones. One farm operates in one farming region. The area of a farming region may vary from 40 to 120 thousand ha across the study area (Lysanova 2001). Collated climatic data were averaged within one farming region. Then, data on both crops and climates averaged for 1966–2009 (with some breaks in crop data primarily during ‘perestroika’) were correlated as regression models, which are spatial relationships between climatic indices, crop range and yields.

The current ranges of the AMI and GDD indices used to build linear regression models extend from 2 to 4.5 for AMI and from 900 to 1500 °C for GDD (table 1). In 2080, the GDD model predictor is expected to range from 1650 to 2000 °C in the B1 moderate climate and from 1650 to 2400 °C in the harsh A2 climate (table 1). To validate the crop models for climate ranges outside current Siberian climate norms, we calculated crops for current climate analogs in southern European Russia and the Ukraine (Sirotenko and Pavlova 2003), thus representing future Siberian climates, and then compared our model predictions with actual crops in these regions (table 3). The results shown in table 3 demonstrate that the models predict reasonably well crops harvested in the current climates of European Russia and the Ukraine. These results show that our models are statistically reliable and are applicable for a GDD range of up to 2200 °C and an AMI of up to 6.0, which is 30% greater than the current Siberian agroclimatic range.

To assess the ‘linearity of crop model’ assumption, the Fisher criteria are applied at 1% and 5% significance (table 4). The F-values for eight out of nine models are greater than the theoretical values, demonstrating the viability of the
These crop yield models are applied to climatic indices in different time frames: pre-1960; 1960–90; 1990–2010 (using observed data); and in 2020 and 2080 climates (using climate change scenarios) to predict potential crop transformation for 150 years in a changing climate. Climatically potential crops are restricted by soil potential, which is accepted as limited by sufficiently developed and fertile soils in the southern taiga, located north of subtaiga and forest-steppes (Lysanov 2001). Thus, we use the northern border of the southern taiga as limiting potential agriculture.

3. Results

January and July temperature and AMI trends were analyzed from 1961 to 2010 based on 63 regressions (3 climatic constraints by 21 stations) in agricultural lands in southern Krasnoyarsk Kray and Khakassia (10 stations within 51–55°N) and Tyva (11 stations south of 51°N). The temperature trends were positive and showed that north of 51°N, January temperatures increased by 1–2 °C and July temperatures increased by 0.7–1.5 °C over the last 50 years. In Tyva, both the January and July temperature increases were two times greater, 2–4 °C and 1.4–3.2 °C, respectively (figure 2).

The significance of these trends was as follows. In Tyva, all July temperature trends were significant; six out of ten January temperature trends were significant at \( p < 0.05–0.1 \). In Khakassia and Krasnoyarsk Kray, five out of 11 July temperature trends were significant at \( p < 0.05–0.1 \) and no January temperature trends were significant at \( p < 0.05–0.1 \). The July temperature trend averaged for the study area (figure 2, upper) was significant at \( p < 0.01 \); the January temperature trend averaged for Tyva (figure 2, lower) was significant at \( p < 0.02 \); the January temperature trend averaged for Krasnoyarsk Kray and Yakassia (51–55°N) (figure 2, middle) was not significant at \( p < 0.1 \). The AMI increase trends were significant at \( p < 0.05–0.1 \) for four out of eight stations; the AMI decreases were significant at \( p < 0.05–0.1 \) for seven out of 13 stations.

### Table 3. Crop yields harvested and predicted using our crop models for selected crops. The table was composed from data of Gumeniuk et al (2010) for Ukraine and data of Vavilov (1986) for European Russia.

| Crop          | Ukraine GDDs | AMI (center ha\(^{-1}\)) | AMI (center ha\(^{-1}\)) |
|---------------|--------------|---------------------------|---------------------------|
| Grain         | Steppe 2500  | 3.3                       | 25–45                     | 32                        |
|               | Forest-steppe| <3.3                      | 30–50                     | 26                        |
| European Russia| Steppe 2200  | >3.3                      | 25–35                     | 28                        |
|               | Forest-steppe| <3.3                      | 15–20                     | 21                        |
| Barley        | Steppe 2500  | >3.3                      | 20–30                     | 19                        |
|               | Forest-steppe| <3.3                      | 25–35                     | 19                        |
| Maize (silage)| Steppe 2200  | >3.3                      | 800–1000                  | 500                       |
|               | Forest-steppe| <3.3                      | 500–600                   | 400                       |
| Potato        | Steppe 2500  | >3.3                      | 175–225                   | 200                       |
|               | Forest-steppe| <3.3                      | 225–300                   | 150                       |
| European Russia| Steppe 2200  | >3.3                      | —                         | —                         |
|               | Forest-steppe| <3.3                      | 150–200                   | 110                       |

### Table 4. Statistical model parameters for various crop yields. (Note: \( a + b \times \text{AMI} + c \times \text{GDD} = W \) (center ha\(^{-1}\)); \( r^{**} \)—correlation coefficient between GDD and AMI; italic—a theoretical value of \( F \)-criteria; bold—not significant.)

| Crop name         | Intercept \( a \) | Slope \( b \) | Slope \( c \) | \( R^2 \) adj. st.err. | \( N \), \( p \) | \( F \), df, 1%, (5%) | \( r^{**} \) |
|-------------------|-------------------|---------------|---------------|-------------------------|----------------|-----------------------|-------------|
| Grain             | 7.92              | −3.45         | 0.011         | 0.43; 2.7; 29; 0.000    |                | \( F(2, 26) = 11.718 \) | 0.15        |
|                   |                   |               |               |                         |                | 5.52                  |             |
| Spring wheat      | 15.05             | −7.15         | 0.017         | 0.68; 3.4; 27; 0.000    |                | \( F(2, 24) = 29.051 \) | 0.06        |
|                   |                   |               |               |                         |                | 5.61                  |             |
| Oatmeal           | 3.86              | −3.94         | 0.0163        | 0.52; 2.8; 29; <0.000   |                | \( F(2, 26) = 15.712 \) | 0.14        |
|                   |                   |               |               |                         |                | 5.53                  |             |
| Barley            | 14.5              | −3.61         | 0.0073        | 0.52; 2.4; 25; <0.000   |                | \( F(2, 22) = 13.812 \) | 0.07        |
|                   |                   |               |               |                         |                | 5.72                  |             |
| Forage root plants| −334.5            | −50.7         | 0.469         | 0.20; 62; 15; <0.100    |                | \( F(2, 12) = 2.7703 \) | 0.37        |
|                   |                   |               |               |                         |                | 6.93 (3.88)           |             |
| Potato            | −29.10            | −7.86         | 0.1062        | 0.31; 17; 31; <0.002    |                | \( F(2, 28) = 7.6384 \) | 0.26        |
|                   |                   |               |               |                         |                | 5.45                  |             |
| Silage            | −7.45             | −96.77        | 0.356         | 0.67; 30.4; 15; <0.000  |                | \( F(2, 12) = 15.314 \) | 0.37        |
|                   |                   |               |               |                         |                | 6.93                  |             |
| Hay               | 6.9               | −4.2          | 0.0168        | 0.49; 2.0; 30; <0.000   |                | \( F(2, 27) = 15.099 \) | 0.59        |
|                   |                   |               |               |                         |                | 5.49                  |             |
| Berries           | −59.0             | −11.0         | 0.077         | 0.48; 5.6; 11; <0.031   |                | \( F(2, 8) = 5.5965 \) | 0.38        |
|                   |                   |               |               |                         |                | 8.65 (4.46)           |             |
Figure 2. (A) Temperature trends for July (upper) in the south of Krasnoyarsky Kray and Khakassia (51–55°N) and Tyva (south of 51°N), and trends for January in the south of Krasnoyarsky Kray and Khakassia (middle) and Tyva (lower). In Tyva, south of 51°N, all July temperature trends were significant and six out of ten January temperature trends were significant at $p < 0.05–0.1$. In Khakassia and Krasnoyarsky Kray, north of 51°N, five out of 11 July temperature trends were significant at $p < 0.05–0.1$ and no January temperature trends were significant at $p < 0.05–0.1$. The July temperature trend averaged for the study area (shown in the upper figure) was significant at $p < 0.01$; the January temperature trend averaged for Tyva (shown in the lower figure) was significant at $p < 0.02$; the January temperature trend averaged for Krasnoyarsky Kray and Kakassia (51–55°N) (shown in the middle figure) was not significant at $p < 0.1$.

(B) Annual moisture index trends south of 55°N. Blue points mark the moisture increase four out of eight trends were significant at $p < 0.05–0.1$) and orange points mark the moisture decrease (seven out of 13 trends were significant at $p < 0.05–0.1$).

The rainfall pattern was complicated by 2010 over the complex topography in the south (Tchebakova et al 2011b).

In general, the AMI trends showed increased moisture or remained stable supporting the forested portion of the forest-steppe zone in Krasnoyarsky Kray and Khakassia. In Tyva, AMI trends showed increasing dryness, especially in the steppe zone in southern and south-eastern portions of Tyva (figure 2), thus promoting steppe vegetation over forest-steppe.

The classification of agri-regions for warmth supply over the study area is given in table 1 and figure 3 (Ivanov 1994). In the current climate, four cold regions (from severe to moderately cold), which are colder than 900°C of GDD$_5$, are not suitable for farming except in greenhouses, or by applying special agricultivation techniques, or by taking advantage of topographic features (southern slopes or river valleys). Regular farming becomes possible in thermal conditions of GDD$_5 > 900$°C (Sinitsyna et al 1973). Optimal combinations of heat and water for crops already exist in the current taiga zone and are predicted to shift further northwards under warming. However, forest soils may not be suitable for farming. Soils, being a product of the interaction between geology, climate and vegetation, evolve for a much longer time when compared with climate and vegetation change.

In the contemporary climate, the classification of local agri-regions accounts for nine warmth classes, only five of which are suitable for farming: from cool to moderately warm (table 1). The last warmth class ‘moderately warm’ appeared in 1991–2010 and occurs in 0.1% of the total study area, 2556440 km$^2$, so in about 2500 km$^2$, and occurs in the heart of the two major basins—the Minusinsk and Tyvan. During the last half of the century, warm lands suitable for farming increased from 22 to 30% of the total studied area. By 2020, warmth-based potential farming lands would increase by 39% (scenario B1) to 34% (scenario A2) and correspondingly 58% to 80% by 2080 (table 1(A)). By the end of the century, the dryness of the climate is predicted to increase and lands with insufficient moisture and drylands will account for 18% (scenario B1) to 30% (scenario A2) of the total area, while, in comparison, by 2010, these lands account for only 5% (table 1(B)). The combination of warmth and moisture conditions favorable for farming, GDD$_5 > 900$°C and AMI < 4.0, is realized in 35–45% of the entire study area for the historical period, pre-1960–2010, and would occur in 50–85% of the area in 2020–80 (table 1(C)).

The climatic ranges of some crops are mapped by coupling their limits for warmth requirements (table 2) with GDD$_5$ maps for current (1990–2010) and 2080 climates (figure 4).
Some traditional crops (spring wheat, winter wheat, maize (silage), oatmeal, barley, millet) and some new crops, currently nonexistent, are considered. By the end of the century, the climatic range of traditional crops would greatly expand, up to the Arctic circle, about 10°, or 1000 km, northwards. This expansion would allow for shifting wheat farming northward, theoretically at a rate of 150 km a decade, although, as was mentioned above, real soil conditions would limit agricultural introduction to about 500 km to the north of its current position. The 2080 climate is predicted to be very warm in the south and would allow for the introduction of sunflower (seeds), late wheat, rice, maize (grain), sugar beets, beans, late millet, soya beans and exotic crops, such as European varieties of grape, although their survival will be determined by winter conditions. Due to the dry climate, farming would require additional water.

**Grain crop trends** (figure 5) showed that with contemporary warming for the last 45 years, crop production increased by about 5–7 centners ha$^{-1}$ under sufficient moisture regimes in forest-steppe ecosystems and was reduced by 8–10 centner ha$^{-1}$ as the climate became dryer in steppe regions.

**Statistical crop yield models** for the most important crops in Siberia are given in tables 3 and 4. Crop yields are strongly related to warmth and water supplies with determination coefficients of 0.43–0.68 except for potato ($R^2 = 0.31$), which depends to a greater extent on soil climate and cultivation techniques than on the surface climate. The models coupled with the future B1 and A2 2080 climates showed that grain crop production may increase from 20 to 35 centner ha$^{-1}$; forage silage crop production may increase from 300 to 600 centner ha$^{-1}$; potato crop production may increase from 100 to 200 centner ha$^{-1}$; and berry crop production may increase from 10 to 60 centner ha$^{-1}$ by 2080. Sirotenko et al (2007) calculated an increase in grain of as much as 5 centner ha$^{-1}$ for the last 30 years, which is comparable to our estimate of a 15 centner ha$^{-1}$ increase for 1990–2080.

Two traditional crops (spring wheat and maize for silage) and new crops currently nonexistent (maize for seed and grapes) are used as case studies. Grain and silage production maps are depicted coupling the models (table 3) with GDDs and AMI maps in the two case studies (figure 6). Potential optimal climatic conditions characteristic of high crop yields at all time slices have been found over large areas in the southern taiga at about 60°N and in smaller areas in the south-east corner of the Minusinsk basin. Steppe and forest-steppe regions of the Minusinsk basin are in a special warm and moist climate on fertile soils, located in the foothills of the Sayan mountains known as a famous granary where farming developed a variety of possible crops, including those rare in central Siberia, such as open-air grown tomatoes, watermelons, and horticulture.
Figure 4. Potential climatic ranges (green) of traditional and new crop (italic) species in central Siberia in the 2010 and HadCM3 B1 and A2 2080 climates.

Figure 5. Grain crops trends, in centner ha\(^{-1}\), for 1966–2009 in the forest-steppe zone (green, three farming regions) and steppe zone (red, three farming regions). The trends are significant at \(p < 0.04–0.10\) in forest-steppe regions and are significant at \(p < 0.001–0.005\) in steppe regions. With warming, crop production increases with sufficient moisture in forest-steppe and decreases as the climate becomes dryer in steppe. Each of the six symbols represents one farming region.

seen from figure 6, the southern taiga regions have promising potential for cultivation in a warmer future, although currently limited cultivated lands taken from the forest are used for regular farming.

4. Discussion

Russia’s agriculture in general benefits from contemporary warming due to increased precipitation in both summer and winter and milder winters resulting in a longer growing season favoring phenological phases (Sirotenko and Gringof 2006). In particular, central Siberia may benefit from current climate warming: the stable positive trends of both summer and winter temperatures showed increases of 2 and 4°C for 50 years correspondingly, which have prolonged the growing season by one month since 1960, and a precipitation increase by about 10% from 1990 to 2010. Some extreme southern regions experienced 10–20% less precipitation from 1990 to 2010 compared to the baseline precipitation. Since 1997, 20–40 centner ha\(^{-1}\) of large grain crops have been collected, and from 2007 to 2011, most farming regions in Krasnoyarsk Kray harvested 50–60 centner ha\(^{-1}\), particularly in the moist western regions (www.topnews24.ru/news/headlines/44566/; www.redom.ru/news/16979/).

As climate warms and dries as predicted from climate change scenarios, northern vegetation habitats (tundra, forest-tundra, and taiga) will decrease from 81.5% to 52.5%, enabling southern habitats (forest-steppe, steppe and semidesert) to expand from 18.5% to 47.5% (Tchebakova et al 2009). At least 50% of central Siberia may become climatically suitable for farming by the end of the century according to the moderate B1 scenario and even larger—85%—according to the harsh A2 scenario. The northern border of farming may shift northwards as far as the Arctic Circle. However, forest soils may not be suitable for farming. Soils, being a product of the interaction of climate and vegetation, evolve for a much longer time than climate and vegetation change. In our model, predictions of potential climate-based agriculture are restricted by the soil potential, so only steppe, forest-steppe and southern taiga soils allow for farming.

Agricultural ecosystems are composed of annual or perennial plants (except multi-year hay grasses) and therefore...
respond to climate change with no inertia. Humans may take advantage of this fact and steadily shift farming northward based on agricultural potential change in a changing climate.

As the climate warms more warmth-loving varieties of the same Siberian crops may be used for farming. New crops may also be introduced if winter conditions allow. For example, some far-eastern grapes have been introduced and have acclimatized in central Siberia on their own merits to survive the cold winter, because they evolved in far-eastern monsoon climates with cold winds from the mainland in winter. In the predicted warmer Siberian climate, maize could be planted to yield grain. In the 1960s, attempts were made during the extensive cultivation of virgin lands in West Siberia; however, that climate was not suitable for this warmth-loving crop, and the experiment failed. The virgin steppe lands degraded under powerful human invasion and were lost to pasture land for many years and have never fully recovered.

The climatic resources of Siberia provide the potential to grow a great variety of crops, primarily basic crops: spring wheat, winter rye and wheat, cereals (oats, buckwheat, barley), early ripe legumes (peas); forage—forage grains (millet, barley, oats, vetch) and root plants; annuals—maize for silage, sunflower silage and seeds; perennials—forage crops, legumes (lucerne, clover, sainfoin, melilot); and grasses (couch-grass, timothy-grass). In a warmer climate, with a prolonged growing season, productive lands in southern Siberia may become suitable for introducing new warmth-loving crops: melons, gourds, fruits and berries. Therefore, some adaptation measures of Siberian agriculture to climate warming would be to farm these crops, which would also decrease their import and transportation costs. Additionally, southern Siberia may become a land for farming oil crops (rape seed, maize grain, soya beans, etc), which could be used for biofuel production and thus promote the development of a biofuel industry in Siberia.

The future climate is predicted to be dry, thus farming would require additional water, so another adaptation measure would be the necessity of irrigating farming. This would be the prevailing type of farming in southern Siberia. The development of a broad irrigation infrastructure should be shortly started in the perspective of adaptation to climate change. Due to the availability of major Siberian rivers (Ob, Yenisei, Lena) with their numerous tributaries, southern Siberia has a high irrigation potential; water will not be a limiting factor for irrigating farming. Additionally, adaptation measures for the effects of extreme climate events (flooding, droughts, frost, etc) on food security may mean moving food and farm land reserves beyond the risk zone (Sirotenko and Gringof 2006).

These adaptation measures to the potential negative (and positive) effects of climate warming would promote the stable development and well-being of southern Siberia’s regions.

5. Major conclusions

- For half a century, from 1960 to 2010, summers have increasingly become 0.7–1.5 °C warmer and winters have become 1–2 °C warmer in the northern farming regions of the Minusinsk basin (Krasnoyarsky Kray and Khakassia), and both summers and winters have become two times warmer 1.4–3.2 and 2–4 °C, correspondingly, in the southern farming regions in Tyva. The pattern of moisture change over the study area was complex with increased moisture in the forest-steppe zone and decreased moisture in the steppe zone.
- 50–85% of central Siberia is predicted to be climatically suitable for agriculture at the end of the century although potential croplands would be limited by the availability of suitable soils within the steppe, forest-steppe, subtaiga and southern taiga zones.
Climatic factors control crop distribution and production in southern Siberia ($R^2 = 0.43–0.68$).

Crop production may increase twofold as the climate warms during the century.

Traditional crops (grain, potato, maize for silage) could gradually shift as far as 500 km northwards (about 50–70 km/decade) and new crops (maize for grain, apricots, grapes, gourds) could be introduced in the far south, depending on winter conditions, and these would necessitate irrigation in the drier 2080 climate.

Agriculture in central Siberia would likely benefit from climate warming.

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**References**

Battisti D S and Naylor R L 2009 Historical warnings of future food insecurity with unprecedented seasonal heat Science 323 240–4

Baranchikov Y N and Kondakov Y P 2002 Siberian moth outbreaks as a factor of the agricultural expansion of taiga territories in Siberia Proc. All-Russian Conf. ‘Sanitary state and a complex of protection measures for the forest after fire impacts in 1972’ (Ioshkar-Ola, 2–3 October) pp 10–2

Budyko M I 1974 Climate and Life (New York: Academic) p 512

Dokuchaev V V 1882 On the issue of Siberian chernozem (St Petersburg, March 1882) (in Russian)

Dronin N and Kirilenko A 2010 Climate change, food stress, and security in Russia Reg. Environ. Change 11 S167–78

Ewert F, Rounsevell M D A, Reginster I, Metzger M J and Leemans R 2005 Future scenarios of European agricultural land use. I. Estimating changes in crop productivity Agric. Ecosystem. Environ. 107 101–16

Groisman P Y et al 2007 Potential forest fire danger over Northern Eurasia: changes during the 20th century Global Planet. Change 56 371–86 (Special NEESPI Issue)

Gumeniuk K, Mishchenko N, Fischer G and van Velthuizen H 2010 Agro-Ecological Assessment for the Transition of the Agricultural Sector in Ukraine. Methodology and Results for Baseline Climate (Laxenburg: IIASA Publication) p 58

IPCC 2007 Summary for policymakers Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Avert, M Tignor and H L Miller (Cambridge: Cambridge University Press) pp 390–562

Koroljeva I E, Vilchesvakaya E V and Ruohovich D I 2003 Digital Arable Land Map (Moscow: Laboratory of Soil Information of the Dokuchaev Soil Institute) (in Afonin A N, Greene S L, Dzyubenko N I and Frolov A N (eds) 2008 Interactive Agricultural Ecological Atlas of Russia and Neighboring Countries. Economic Plants and their Diseases, Pests and Weeds (available online at: www.agroatlas.ru))

Lebedev V I and Populiahk Yu G (ed) 2005 Atlas Economical Potential of Republic of Tyva (Kyzyl: TuvIKOPR SB RAN) p 60

Lysanovna G I 2001 Landscape Analysis of Agri-Natural Potential of Geosystems (Irkutsk: Institute of Geography SB RAN) pp 187 (in Russian)

Lysanovna G I and Artemiukh V N 2006 Landscape-ecological studies of geosystems of the Minusinsk basin Geogr. Natural Res. 4 65–9

Meshcherskaya A V, Mirvis V M and Golod M P 2011 The drought of summer 2010 against the background of long-term changes in the aridity over bread-basket region in the European territory of Russia Trans. Voeikov Main Geophys. Obs. 563 1–27 (in Russian)

Mueller C, Cramer W, Hare W L and Lotze-Campen H 2011 Climate change risks for African agriculture Proc. Natl Acad. Sci. USA 108 4313–5

Randall D A et al 2007 Climate models and their evaluation Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Avert, M Tignor and H L Miller (Cambridge: Cambridge University Press) pp 590–662

Reference Book on Climate of the USSR 1967–1971 (Leningrad: Gidrometeoizdat)

Reference Books on Monthly Climate of Krasnoyarsky Kray, Khakassia, and Tyva 1960–2010 (Novosibirsk: Gidrometeoizdat)

Reference Books on Statistical Data. Agriculture of Rep. Khakassia 1966a–2009 (Abakan: Roskomstat)

Reference Books on Statistical Data. Agriculture of Krasnoyarsky Kray 1966b–2009 (Krasnoyarsk: Roskomstat)

Reference Books on Statistical Data. Agriculture of Rep. Tyva 1986–2009 (Kyzyl: Roskomstat)

Shotsky V P (ed) 1977 Atlas of the south of Krasnoyarsky Kray Maps for Planning Agriculture (Moscow: GUGK) p 40

Sinitsyna I I, Goltsberg I A and Strumnikov E A 1973 Agroclimatology (Leningrad: Gidrometeoizdat) p 344 (in Russian)

Sinyagin I A and Tyutyanukova A I (ed) 1978 1978 Reference Book for an Agronomist of Siberia (Moscow: Kolos)

Sirotenko O D and Gringoif I G 2006 Estimation of anticipated climate change impacts on agriculture of the Russian Federation Russ. J. Meteorol. Hydrol. 8 90–103 (in Russian)

Sirotenko O D, Gruza V G, Rankova E Ya, Abashina E V and Pavlova V N 2007 Contemporary climate change of warmth, moisture and productivity of the agrisphere of Russia Russ. J. Meteorol. Hydrol. 32 743–56 (available online at: www.agroatlas.ru)

Sirotenko O D and Pavlova V N 2003 Evaluation of climate change impacts on agriculture using the method of spatio-temporary analogs Russ. J. Meteorol. Hydrol. 8 89–99 (in Russian)

Soja A J, Tchekabova N M, French N H F, Flannigan M D, Shugart H H, Stocks B J, Sukhinin A I, Parfenova E I, Chapin F S III and Stackhouse P W Jr 2007 Climate-induced boreal forest change: Predictions versus current observations Glob. Planet. Change 56 274–96 (Special NEESPI Issue)

Steffen W, Sims J, Walcott J and Laughlin C F 2011 Australian agriculture: coping with dangerous climate change Reg. Environ. Change 11 S205–14

Tao F, Zhang Zh and Yokozawa M 2011 Dangerous levels of climate change for agricultural production in China Reg. Environ. Change 11 S41–8

Tchekabova N M and Parfenova E I 2011 Potential land cover change in Siberia predicted by Siberian bioclimatic model...
Regional Environmental Changes in Siberia and Their Global Consequences (Berlin: Springer) submitted
Tchebakova N M, Parfenova E I, Lysanova G I, Shvetsov E G and Soja A J 2011a An agroclimatic potential in southern Siberia in a changing climate during the XXI century Paper Presented at the Annual EGU Assembly (Vienna, April) (www.neespi.org/web-content/meetings/EGU_2011/Tchebakova.pdf)
Tchebakova N M, Parfenova E I and Soja A J 2009 Effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate Environ. Res. Lett. 4 045013
Tchebakova N M, Parfenova E I and Soja A J 2011b Climate change and climate-induced hot spots in forest shifts in central Siberia from observed data Reg. Environ. Change at press (doi:10.1007/s10113-011-0210-4)
Tchebakova N M, Rehfeldt G E and Parfenova E I 2010 From vegetation zones to climatypes: effects of climate warming on Siberian ecosystems Permafrost Ecosystems, Siberian Larch Forests ed A Osawa, O A Zyryanova, Y Matsuura, T Kajimoto and R W Wein (Dordrecht: Springer) chapter 22, pp 427–47
Vavilov P P 1986 Plant-Growing (Moscow: Agropromizdat) p 512
Wright C K, de Beurs K M, Akhmadiyeva Z K, Groisman P Y and Henebry G M 2009 Recent temperature and precipitation trends in Kazakhstan reveal significant changes in growing season weather Environ. Res. Lett. 4 045020