Global Food Security 3 (2014) 133–141

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

The potential of Russia to increase its wheat production through cropland expansion and intensification

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ARTICLE INFO

Article history:
Received 15 August 2014
Received in revised form
3 October 2014
Accepted 3 October 2014

Keywords:
Agriculture
Crop production
Land abandonment
Recultivation
Yield gap
Russia

ABSTRACT

Russia is a major player in the global wheat market, but extensive unused land resources and large yield gaps suggest that wheat production can be substantially increased. We combined time series of cultivated cropland, abandoned cropland and yield gap estimates to assess the potential production of wheat in European Russia. Current wheat production is constrained by volatile inter-annual precipitation patterns and low applications of nitrogen fertilizers. We demonstrate that modest increases in the crop productivity and the recultivation of the recently abandoned croplands could increase wheat production by 9–32 million tons under rainfed conditions. Increases in the wheat yields, particularly within the fertile black soil belt in southern European Russia, will contribute the major share of the prospective production increases. Frequently recurring droughts, likely exacerbated by future climate change, and adverse market conditions jeopardize the exploitation of the production potentials. Improved adaptation to the volatile climate conditions and substantial institutional and political reforms in the agricultural sector are necessary to leverage the agricultural production potential of Russia.

1. Introduction

The worldwide demand for agricultural products will grow considerably in the coming decades because of increasing populations, changing diets and the increasing use of bioenergy (Tilman et al., 2011; Regmi and Meade, 2013). This increasing demand can be satisfied by expanding cultivated areas, but the ecological and social trade-offs of further land expansion are high in most regions (Lambin et al., 2013). Most future increases in agricultural production are therefore likely to be generated by increasing the output per unit of land, that is, from higher land productivity.

The scope for future increases in land productivity is substantial in many developing and transition countries where the differences between the potential yield under optimum management and the yields that are actually achieved by farmers, i.e., yield gaps, are large (Affholder et al., 2013; Hall et al., 2013; Lu and Fan, 2013; van Ittersum and Cassman, 2013). Reductions in the yield gaps will typically require higher and more efficient input use (fertilizers, pesticides, and water) and improvements in crop management (Evans and Fischer, 1999). Moreover, to decrease yield gaps necessitate investments in infrastructure, education and agronomic research, as well as supportive agricultural policies (Neumann et al., 2010; Tilman et al., 2011; George, 2014).

One country that is of particular interest for increasing the supply of agricultural products is the Russian Federation. Russia has emerged as a leading player in the world grain market; the country was among the top five wheat-exporting countries between 2006 and 2011 (FAO, 2014). Russia can increase its grain production substantially and thus expand its position in the world grain markets because of low yields and large areas of idle former agricultural land (Lioubimtseva and Henebry, 2012). However, it remains elusive how large the untapped grain potentials of Russia are and which environmental trade-offs are associated with land recultivation and intensification.

The dissolution of the Soviet Union in 1991 and the subsequent institutional reforms triggered widespread agricultural land abandonment in Russia (Prishchepov et al., 2012). As a result, vast areas of former cropland can potentially be recultivated. However, a substantial carbon sink developed in the soils and in the successional vegetation on the cropland that was abandoned soon after the dissolution, and the recultivation of these lands would lead to large carbon emissions (Poeplau et al., 2011; Schierhorn et al., 2013).

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http://dx.doi.org/10.1016/j.gfs.2014.10.007

The crop yields in Russia decreased after the dissolution of the Soviet Union, rebounded toward the late 1990s (ROSSTAT, 2014), but remained much lower than the yields that are achieved in comparable natural conditions outside the country (Licker et al., 2010; FAO, 2014). The main reason for the large yield gaps in wheat cultivation are severe limitations of water and nutrient application (Nosov and Ivanova, 2011; Schierhorn et al., 2014), mainly caused by financial and managerial shortcomings at the farm level, as well as institutional shortcomings and adverse infrastructure (Bokusheva et al., 2012).

Here, we estimate the potential of European Russia for wheat production. European Russia produces 75% of Russia's wheat output and provides the bulk of Russian wheat exports (ROSSTAT, 2014). To quantify potential production increases, our specific objectives are first to estimate the production potential of existing cropland by combining cropland data with estimates of yield gaps in wheat cultivation. Second, we quantify the production potential from recultivating abandoned cropland under consideration of the carbon emissions that are released from the successional vegetation and soils. Finally, we discuss the production potential in light of volatile climate conditions and the structural and socio-political constraints that may jeopardize future increases in the wheat production in Russia.

2. Land endowment

Official agricultural inventory statistics report a total sowing area of 77 million hectares (Mha) for Russia in 2011, down from 118 Mha in 1990 (ROSSTAT, 2014, Fig. 1). This implies a decrease in the sowing areas by 35% or 41 Mha, equivalent to the entire sowing areas in 2010 of France, Germany and Spain combined (Eurostat, 2013). Official inventory statistics of the sowing area are reliable data of land abandonment for Russia (Ioffe et al., 2004; Nefedova, 2011), and match well with the remote sensing estimates of abandoned agricultural lands (Alcantara et al., 2013) and of sowing areas (de Beurs and Ioffe, 2013).

The contraction of cropland in Russia has been triggered by the liberalization of previously subsidized input and output prices, poorly functioning land markets, and increasing international competition (Lerman and Shagaida, 2007; Liefert and Liefert, 2012; Prishchepov et al., 2013). In particular, the profitability of livestock production decreased after the dissolution of the Soviet Union (Lioubimtseva and Henebry, 2012), mainly driven by the abrupt elimination of state subsidies to the livestock sector. In response, the number of cattle decreased by 65%, from 57 million in 1990 to 20 million in 2012 (ROSSTAT, 2014). The contraction of the livestock production was coextensive with the sharp decrease in fodder crops (27 Mha or 61%, Fig. 1). Grains other than wheat (e.g., barley and rye), which are partly used as fodder for livestock, also decreased substantially between 1990 and 2012 (19 Mha or 51%, Fig. 1). The area that was cultivated with wheat remained fairly stable during this period mainly because wheat has been the main staple crop in Russian food consumption and due to the emerging export opportunities of wheat.

European Russia contained 72% or 55.7 Mha of the total sowing area of Russia (77 Mha) in 2011 (ROSSTAT, 2014). The sowing areas cluster along the fertile black soil belt that stretches from southern to eastern European Russia (the hatched area in Fig. 2). Fewer sowing areas are found outside the black soil belt in temperate European Russia (north of latitude 55°; Fig. 2), where the cropland suitability is considerably lower (Schierhorn et al., 2013). The sowing area in European Russia decreased by 33% or 27.2 Mha after the dissolution of the Soviet Union (ROSSTAT, 2014). The highest rates of decrease in the sowing areas occurred in the region north of the black soil areas. In contrast, the smallest decreases occurred within the black soil belt in southern European Russia, which is also the primary breadbasket of Russia. Most of the post-Soviet abandonment of cropland occurred soon after the dissolution of the Soviet Union (Schierhorn et al., 2013).

3. Wheat yields and wheat yield gaps

The fading state support for agriculture and the liberalization of markets along with weak institutional conditions after the dissolution of the Soviet Union contributed to the strong reduction of the agricultural input use (mainly fertilizers) in Russia, particularly during the early 1990s (Rozelle and Swinnen, 2004). In combination with poor weather conditions during the 1990s (Liefert and Liefert, 2012; Schierhorn et al., 2014), the average wheat yields decreased from 1.93 t/ha between 1990 and 1992 to

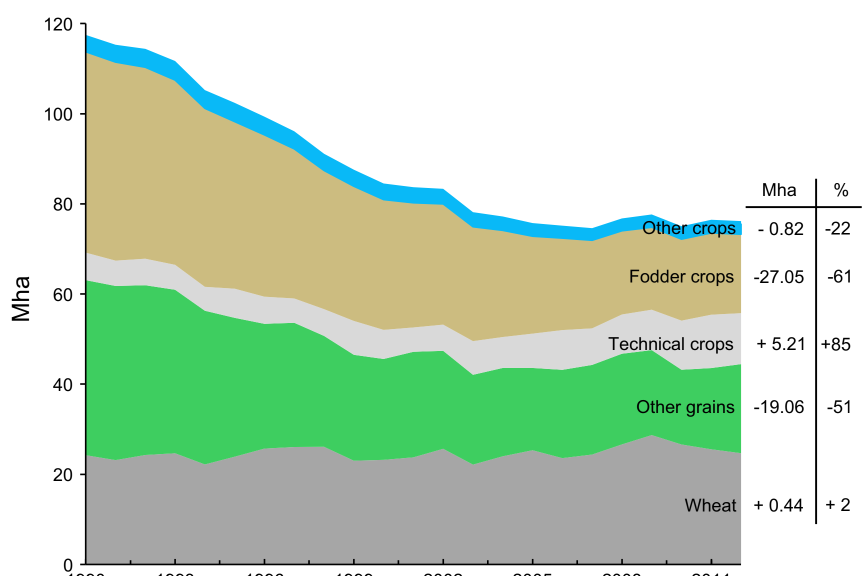

Fig. 1. Sowing areas (million hectares, Mha) in Russia. Per cent and absolute change between 1990 and 2012 on the right. Other crops: potatoes and vegetables; fodder crops: annual and perennial grasses and root vegetables; technical cultures: sunflower, sugar beet, soybean, and rapeseed; other grains: barley, rye, and oat. The data are from ROSSTAT (2014).

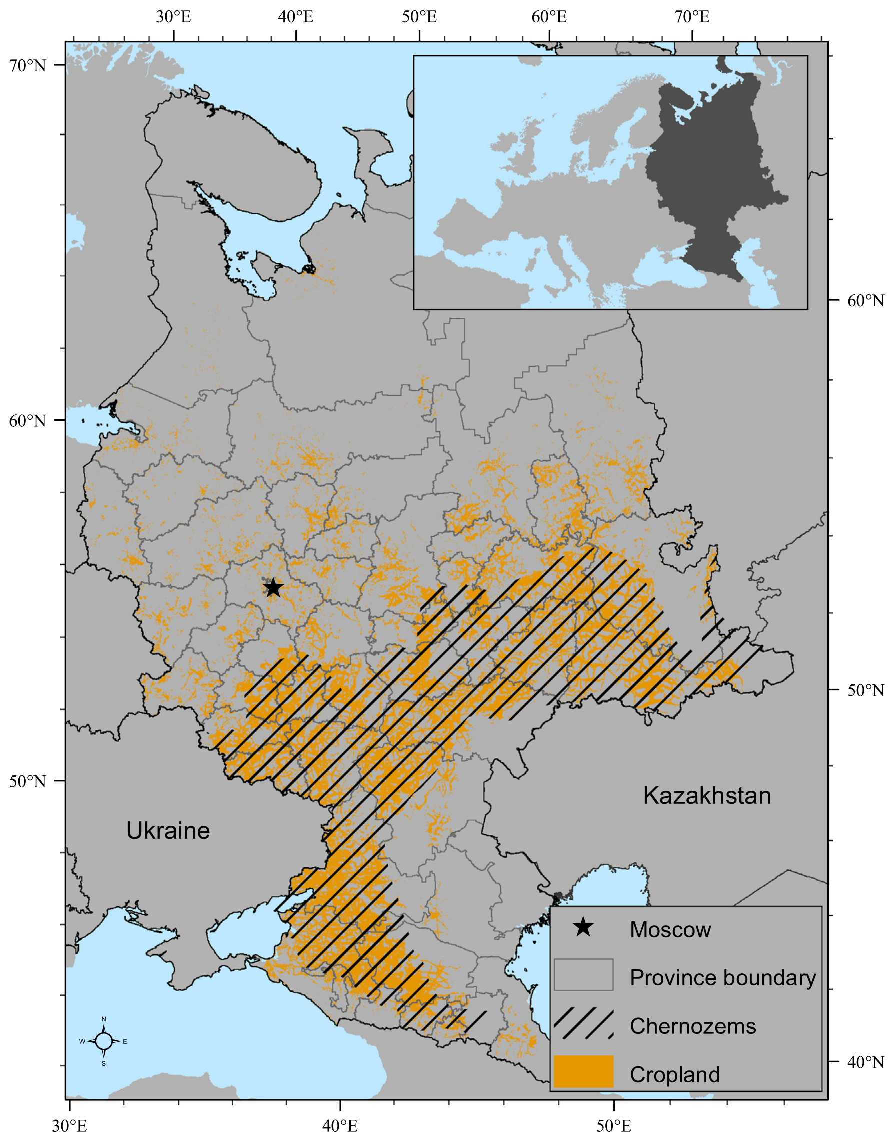

Fig. 2. Distribution of croplands in 2011 and the location of the black soil belt in European Russia. The cropland data are from Schierhorn et al. (2013).

1.49 t/ha between 1994 and 1996, a decrease of 23% (Fig. 3). Fig. 3 also reveals the high inter-annual yield variability that was mainly caused by the volatile weather conditions, especially in southern European Russia.

In the late 1990s, the wheat yields in Russia began to increase again (Fig. 3), partially as a result of the increase in the agricultural input intensity and higher production efficiency, mainly triggered by the emergence of large, profit-oriented corporate farms with abundant capital (Liefert et al., 2010; Salputra et al., 2013). For example, nitrogen (N) fertilizer application in cereal production surged by 150% between 1999 and 2012, from 16 to 40 kg/ha (Fig. 3). Moreover, better weather conditions after 1998 contributed to the increase in wheat yields in Russia (Liefert and Liefert, 2012; Schierhorn et al., 2014). The wheat yields rebounded approximately to the 1990 level by 2007, although N fertilizer application was applied at only half of the rate during late Soviet times (Fig. 3). The low application rates were compensated for by higher-quality wheat cultivars (Liefert et al., 2010). Nevertheless, the contemporary wheat yields in Russia are three to four times lower than the average yields in Germany and France (FAO, 2014). However, there are also considerable regional differences in the wheat yields across European Russia. For example, in 2008, a year with good weather conditions, the average wheat yields were 3.8 t/ha within the fertile black soil belt in southern European Russia, but only 1.97 t/ha in other areas (ROSSTAT, 2014).

4. Material and methods

We quantified the wheat production that can potentially be achieved in European Russia by assuming different degrees of yield gap closure on existing cropland and by recultivating abandoned croplands with the same assumptions of yield gap closure.

4.1. Estimation of the production potential on existing cropland

We quantified the potential wheat production on existing cropland by gradually increasing the wheat yields towards the potential yield. To obtain the biophysical yield potentials, we simulated plant growth for winter and spring wheat at the provincial (*oblast*) level across European Russia (Schierhorn et al., 2014). We used the Soil and Water Assessment Tool (SWAT), which is a process-based, spatially distributed landscape model that relies on a simplified version of the erosion productivity impact calculator (EPIC, Williams et al., 1989) for plant growth simulation

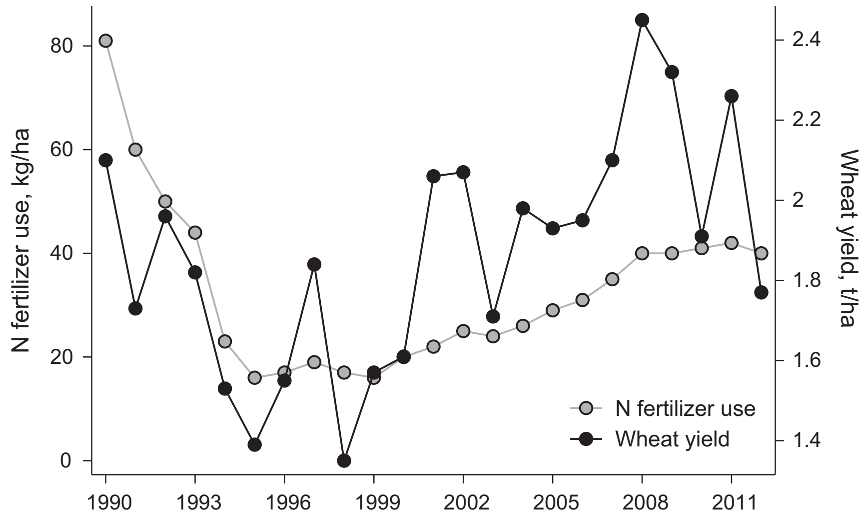

Fig. 3. N fertilizer use (kg/ha) and wheat yields (t/ha) in Russia. The data are from ROSSTAT (2014).

(Arnold et al., 1998). Our SWAT application simulates plant growth based on the reported N application from official statistics and under water-limited as well as irrigated conditions. Otherwise, we enforced optimal growing conditions in the model, that is, without stress for the crops due to weeds, pests and diseases (Neitsch et al., 2005).

In SWAT, the study area is divided into sub-basins based on topography. We selected the 28 sub-basins (one per province) with the largest area of cropland and with more than 25,000 ha under wheat cultivation in 2006. The main input data are the digital elevation model GTOPO30 from the U.S. Geological Survey (USGS), monthly climate data from the Climate Research Unit (CRU, TS 1.0 and 2.0, http://www.cru.uea.ac.uk/cru/data/hrg.htm) were used to generate daily precipitation, temperature, solar radiation and wet-day frequency with the SWAT weather generator (Arnold and Fohrer, 2005), and soil parameters from the Harmonized World Soil Database (FAO et al., 2012). We used the annual wheat yields, N fertilizer use and sowing area of wheat from official provincial-level statistics (ROSSTAT, 2014) to calibrate the SWAT model and we validated the model with data from 1991 to 1994 (Schierhorn et al., 2014). The data on the growing season length of wheat were obtained from the United States Department of Agriculture (USDA, 2013), Rukhovich et al. (2007), and GOSSORT (2014).

The calibrated model was used to simulate wheat yield potentials with an optimal N supply for both water-limited (rainfed) conditions and irrigated conditions (see Schierhorn et al. (2014), for a detailed description of the model calibration and uncertainty assessment). Other measures to increase the yields (e.g., the selection of different wheat cultivars) were not assessed. We simulated the yield potentials separately for all 28 sub-basins in European Russia to better account for the large spatial heterogeneity in environmental conditions. Our simulation period from 1995 to 2006 includes years with sufficient precipitation (mainly after 2000) as well as severe drought years (mainly before 2000).

We used the average reported wheat yields of all of the provinces between 1995 and 2006 to calculate the baseline production. The baseline for cultivated area consists of the average sowing area for grains in all of the provinces between 1995 and 2006 (34 Mha) under the assumption that wheat can potentially be cultivated in the entire grain area. We then multiplied for each province the average wheat yield with the average grain area to generate a baseline output of wheat production (59 million tons, Mt), against which we compared the additional wheat output that can be attained by yield growth on existing croplands. The uncertainty of the wheat yield simulation is visualized with the 95% prediction uncertainty (95PPU) band that represents the model uncertainty excluding the lower and upper 2.5th percentiles of the simulated values (Abbaspour et al., 2007). For the sake of brevity, we reported all of the results using the mean 95PPU of wheat production potential.

4.2. *Estimation of production potential on abandoned cropland*

The expansion of crop production on abandoned cropland is often assumed to be a relatively sustainable way to increase the supply of agricultural products (Campbell et al., 2008; Cai et al., 2010). However, abandoned croplands store considerable amounts of carbon in successional vegetation and soils, depending on the natural conditions and the duration of succession (Post and Kwon, 2000; Kurganova et al., 2014). Carbon sequestration on abandoned croplands in European Russia increased significantly after approximately ten years of abandonment (Schierhorn et al., 2013). Consequently, carbon emissions from recultivating abandoned cropland increase with time since abandonment. Moreover, the recultivation of older successional vegetation is costly because the mature vegetation including soil-penetrating roots must be removed (Larsson and Nilsson, 2005; USDA-FAS, 2008).

We used annual time series of post-Soviet cropland abandonment (Schierhorn et al., 2013) that accounted for the increasing carbon emission and recultivation costs that are associated with recultivation. We assumed that recultivation commences on the recently abandoned cropland and progressively integrates older abandoned fields. Approximately 9.5 Mha (35%) of the total 27.2 Mha of abandoned cropland in European Russia was abandoned after 2000, and we assume that recultivation takes place on these 9.5 Mha because of lower carbon emissions. However, most of these abandoned croplands are located in temperate European Russia, where the share of grain cultivation is low. We assumed that the share of wheat matched the share of grain in the total sowing area in each province, which leaves only 4.4 Mha available for recultivation with wheat. We multiply these 4.4 Mha with the potential yield to generate wheat production potentials on abandoned cropland.

5. Results

We found average relative yield gaps (the ratio of potential minus actual yield to potential yield) of 62–63% (3.14–3.30 t/ha) between 1995 and 2006 for irrigated conditions and substantial but smaller yield gaps for rainfed conditions (44–52% or 1.51–2.10 t/ha). The yield gap analysis revealed that water availability and fertilizer application are critical for increasing wheat yields. However, frequently recurring droughts in the black soil area induced large annual fluctuations in the yield potential.

5.1. Production potential of existing cropland

Under rainfed conditions without N stress, the reduction of the time-averaged wheat yield gap in each province to 60% and 80% of the province's yield potential would increase the baseline wheat output of 59 Mt (see Section 4.1, Fig. 4) by 3 and 23 Mt, respectively. Closing the average yield gap to 60% and 80% of the yield potential under irrigated conditions would generate an additional 30 and 60 Mt of wheat, respectively (Fig. 4). A complete yield gap closure would result in an additional wheat production of 44 Mt under rainfed conditions and 90 Mt under irrigated conditions (for comparison, the United States harvested 62 Mt of wheat in 2012, FAO, 2014). The higher uncertainty of the rainfed estimates in Fig. 4 is caused by the better performance of the crop growth model in simulating potential wheat yields under irrigated conditions (Schierhorn et al., 2014).

Weather conditions – and particularly water availability – during the growing period are crucial for wheat production in rainfed systems in European Russia. The lack of precipitation can severely reduce the crop output, even with an optimal N fertilizer supply, as indicated by the large interannual variation in the wheat production potential for rainfed systems (Fig. 5). For example, the wheat production potential with a complete yield gap closure under rainfed conditions in 1995 (a severe drought year) was 48 Mt or 38% lower than that in 1997 (a year with good weather conditions).

The potential wheat production on existing cropland is substantially higher and less variable in years without water stress (Fig. 4), emphasizing that the expansion of irrigated areas in combination with an optimal N fertilizer supply is a key to increase production and decrease production volatility. While irrigation expansion is unrealistic at a large scale due to water shortages in many locations (Alcamo et al., 2007) and to prohibitive investment costs at the current prices of wheat and irrigation technologies, it can alleviate water stress in areas where irrigation water and investment capital are available.

We found the largest wheat production potential on currently cultivated croplands in the fertile black soil belt (Fig. 6A) where large sowing areas of grain coexist with large yield gaps (Fig. 2).

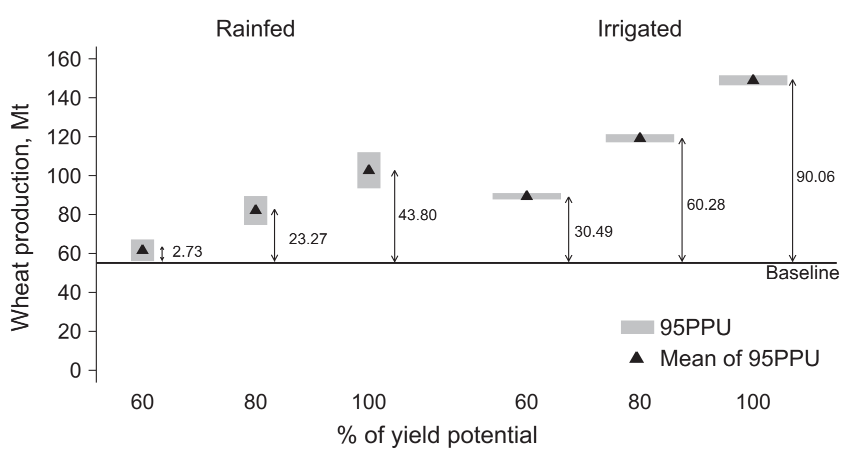

Fig. 4. Wheat production potentials (million tons, Mt) with different degrees of yield gap closure (60%, 80%, and 100%) on existing croplands under rainfed (left) and irrigated conditions (right). The triangles represent the average potentials of the 95% prediction uncertainty (95PPU) in wheat production between 1995 and 2006, the error bars depict the 95PPU in wheat production potential and the arrows indicate the potential additional production.

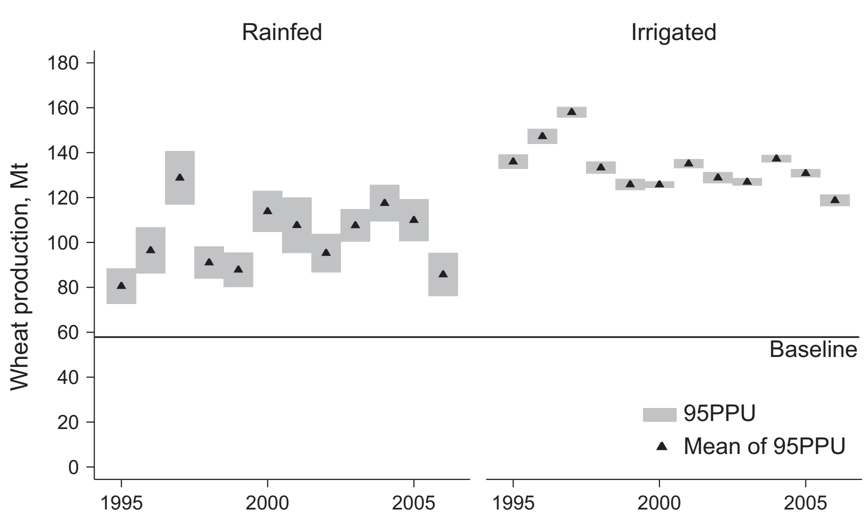

Fig. 5. Annual wheat production potentials (Mt) with 100% of the yield potential on existing croplands under both rainfed (left) and irrigated conditions (right). The error bars depict the 95% prediction uncertainty (95PPU) in wheat production potential.

The production potentials under rainfed conditions on the existing cropland are lower outside the black soil areas because the sowing areas are smaller. Production potentials are also low in some provinces in southern European Russia where the yield gaps under rainfed conditions are small (e.g., Volgograd and Penza, Fig. 6A).

5.2. Production potential of abandoned cropland

Depending on the degree of yield gap closure, the recultivation of all of the abandoned croplands with wheat would increase the wheat production between 23 and 40 Mt under rainfed conditions (Fig. 7A) and between 23 and 58 Mt under irrigated conditions (Fig. 7B), albeit at high carbon emissions and recultivation costs. The recultivation of the 4.4 Mha with low carbon stocks (see Section 4.2) would increase wheat production by 6 Mt with average actual yields between 1995 and 2006 and by 12 Mt with a full yield gap closure under rainfed conditions (Fig. 7A). The spatial distribution of provincial production potentials on the recently abandoned croplands is shown in Fig. 6B. Production increases on the recently abandoned croplands are greatest in temperate European Russia and are lower towards the south.

The additional wheat output for the 4.4 Mha is similar under irrigated and rainfed conditions because water stress is lower in temperate European Russia, where the 4.4 Mha are largely located (Fig. 7A and B). Moreover, the variation in the wheat potential between 1995 and 2006 under rainfed conditions is less volatile in this region (Fig. 8A and B). Therefore, the large production losses due to recurring droughts on the currently cultivated cropland in the southern black soil region may be partially offset by the recultivation of the recently abandoned cropland in temperate European Russia.

5.3. Overall production potential

The overall wheat production potential comprises production from currently cultivated croplands and the recultivation of abandoned croplands under different assumptions of yield gap closure. Most developed countries achieve crop yields of up to 80% of their yield potential (Cassman et al., 2003), and this

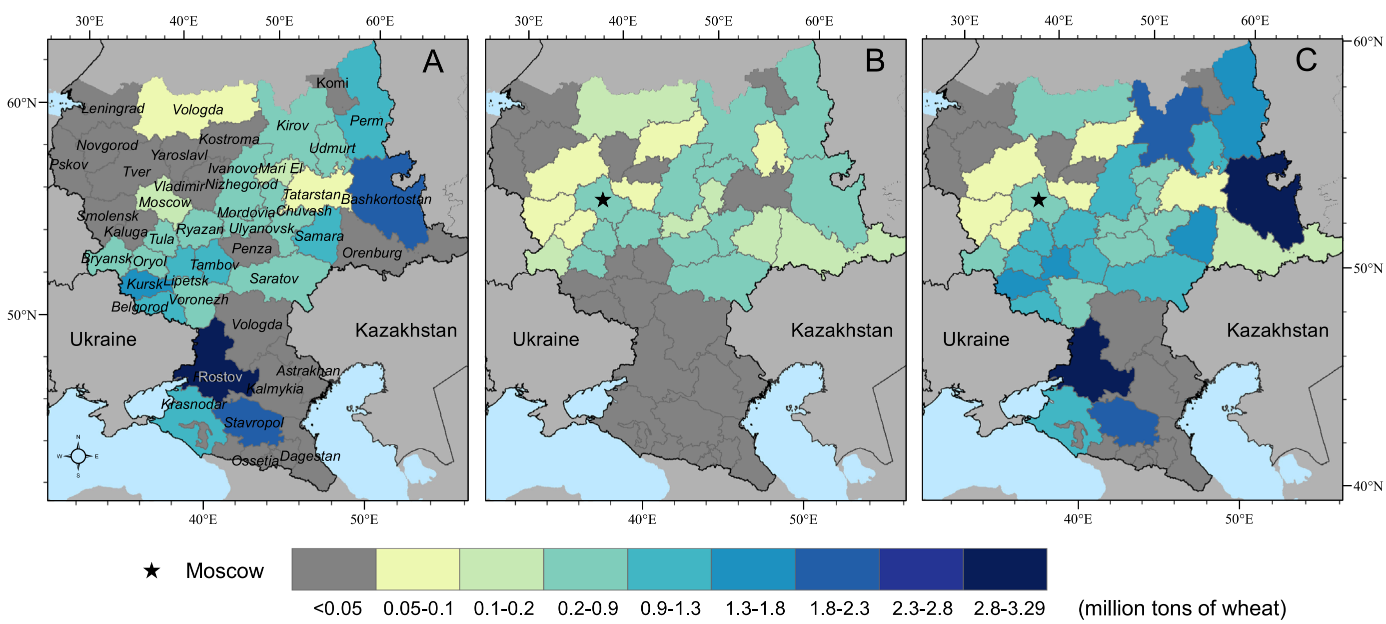

Fig. 6. Spatial distribution of the wheat production potentials (Mt), with 80% of the yield potential under rainfed conditions on existing cropland (A), from the recultivation of the 4.4 Mha of cropland that had been abandoned since 2000 (B), and overall (C).

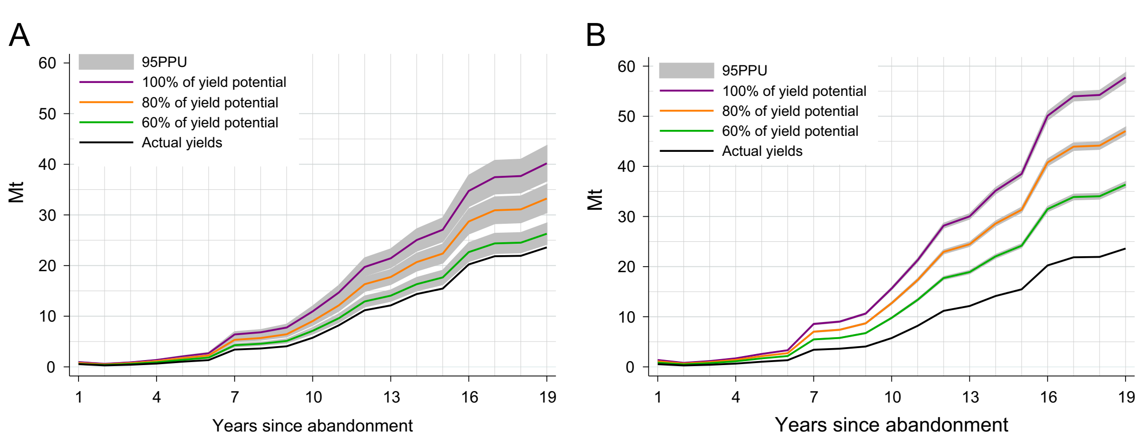

Fig. 7. Wheat production potentials (Mt) with different degrees of yield gap closure on abandoned cropland under rainfed conditions (A) and irrigated conditions (B). The lines indicate the average potentials of wheat production between 1995 and 2006. The years since abandonment, with 2010 as the reference year, capture the production potential on the cropland that had been abandoned since 1990 (e.g., 19 years since abandonment is equivalent to 27.2 Mha of abandoned land; see chapter 2). Note that our approach integrates only a share of the abandoned land (see Section 4.2).

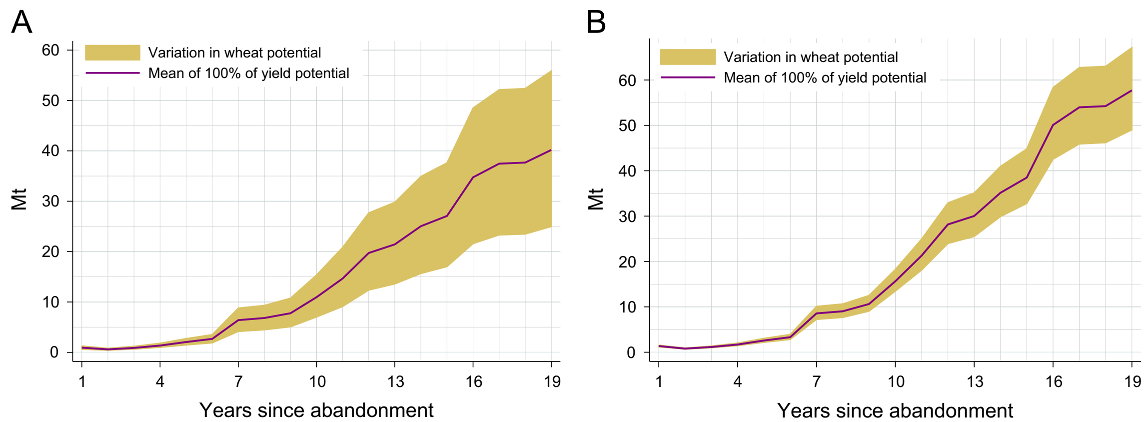

Fig. 8. Variation in the wheat production potentials (Mt) between 1995 and 2006 with full yield gap closure under rainfed conditions (A) and irrigated conditions (B). See the caption of Fig. 7 for an explanation.

characteristic may apply to Russia as well. We therefore assumed that the wheat yields on the currently cultivated croplands and on abandoned croplands increase to 60% and to 80% of the yield potential under rainfed conditions. We excluded the simulated yield potentials under irrigated conditions because current cropping systems in European Russia are almost completely rainfed. Recultivation was restricted to the 9.5 Mha of recently abandoned cropland, of which only 4.4 Mha are available for wheat recultivation in our scenario (see Section 4.2).

Our assumptions about cropland expansion and yield increase resulted in additional production potentials of wheat in the range of 9–32 Mt. Clusters of high wheat potentials are concentrated in southern and northeastern European Russia, where large yield gaps under rainfed conditions co-occur with large areas of unused cropland. The provinces of Stavropol, Rostov, Bashkortostan, and Kirov have the largest untapped production potentials under rainfed conditions for wheat in European Russia (Fig. 6C).

6. Discussion

We demonstrated that European Russian can substantially increase its wheat production and satisfy a substantial share of the projected increase in the wheat demand. Most production increases will likely come from increasing yields on existing croplands and thus avoid carbon emissions from recultivation. We advocate higher production potential on the currently cultivated croplands than recent projections for wheat production in Russia (Liefert et al., 2010; FAPRI-ISU, 2012; OECD-FAO, 2013; Salputra et al., 2013) because we accounted for the large yield gaps. Our projection seems realistic because we assumed only a partial closure of the current yield gaps to 60% and to 80% of the yield potential under the prevailing rainfed conditions. Moreover, we ignored technological progress, which can increase the yield potential by developing improved wheat cultivars (Hall and Richards, 2013).

Our yield gap analysis for Russia is based on calibration of the SWAT model under N-limiting conditions using statistical data for actual nitrogen applications and actual yields. We assumed that the calibrated model can be used to simulate potential yield under conditions without N and water limitation. This assumption requires further testing with experimental data, and hence our simulations of yield gaps should be regarded as initial estimates. However, our potential yields are likely to be conservative because we used a conventional wheat variety from the default SWAT database. Current wheat yields in a biophysically comparable region in Central Germany (Magdeburg Börde) average 8 t/ha (Nehring, 2011) and are thus substantially higher than our simulated potential yields under irrigated conditions in European Russia (about 6 t/ha, Schierhorn et al., 2014). Moreover, the interpolation of monthly weather data to daily data has implications for the quality of yield simulations (van Wart et al., 2013).

Our scenarios regarding the recultivation of idle cropland are conservative because we only included recently abandoned cropland to avoid substantial carbon emissions from recultivating croplands that were abandoned soon after the dissolution of the Soviet Union in the early 1990s. Accounting for the carbon tradeoffs leaves 4.4 Mha available for recultivation, which is lower than previous assessments of the potentially available cropland in Russia (FAO/EBRD, 2008; USDA-FAS, 2008; Lambin et al., 2013). Wheat production on the 4.4 Mha and with average wheat yields from 1995 to 2006 can increase the production by 6 Mt, which is almost four times less than the production potentials on existing croplands and only 19% of the our estimated maximum production potential of 32 Mt. One reason for this modest increase is that most of the 4.4 Mha are located north of the black soil areas, where the environmental conditions are only moderately suitable for wheat production. In other words, higher land productivity will be crucial to increase wheat production in Russia, whereas cropland expansion is only of minor importance if the carbon costs resulting from cropland recultivation would be accounted for.

Nutrient limitation is an important reason for the large yield gaps in European Russia (Schierhorn et al., 2014). Fertilizer use in Russia is still substantially lower than during the late Soviet Union period in the 1980s (ROSSTAT, 2014) and lag far behind that of Western Europe and the U.S. (FAO, 2014). The low input use in Russian grain production most likely indicates structural problems at the farm level, low farm-gate output and high input prices, as well as institutional deficits (Swinnen and Van Herck, 2011; Liefert and Liefert, 2012). Incentives to invest in more inputs depend, *inter alia*, on transparent and persistent institutions and policies, which might ensure a stable return from crop production. However, the country's institutions are still pending somewhere between a centrally planned and a market-oriented economy (Swinnen and Van Herck, 2011; Liefert and Liefert, 2012). Other obstacles for the agricultural sector include outdated rural infrastructure, low public and private investments in agricultural research and development, and a considerable lack of qualified farm labourers and managers (FAO, 2009; Swinnen and Van Herck, 2011). These constraints reduce the profitability and increase the risk of farming and negatively affect the investment behaviour of Russian farms (Bokusheva et al., 2007).

Production risks in Russian agriculture are high for a variety of reasons. First, the volatile climate conditions translate into volatile returns from agriculture in the absence of sound insurance systems to protect against production shortfalls (Dronin and Kirilenko, 2011; Bobojonov et al., 2014) and because Soviet-time irrigation systems have largely deteriorated. Irrigated cropland decreased from 2.3 to 0.9 Mha between 1990 and 2006, a decrease of 61% (ROSSTAT, 2008). Investments in irrigation, particularly in the black soil belt, may considerably reduce the yield volatility and increase incentives to invest in production. Another promising avenue to stabilize and increase yields is plant breeding, e.g., of drought-tolerant crop cultivars (Araus et al., 2002; Howden et al., 2007; Reynolds et al., 2011). However, the research and development of plant breeding by Russian research institutes and private companies is scant and the lack of plant cultivars that are adapted to local conditions remains a major bottleneck in crop production (FAO, 2009).

Second, wheat production is exposed to considerable price risks because Russian grain producers depend on exports and thus on volatile world market prices. The recent high price volatility in the global grain markets has been amplified by government interventions, such as export restrictions in response to the 2010 drought, which aimed to protect domestic consumers from increasing food prices. These export restrictions caused a disconnection between the domestic and world market prices and incurred high costs for Russian grain producers, forcing them to sell wheat far below the world market price (Götz et al., 2013). Such policy interventions have created an unstable and unpredictable business environment that affects the investment behaviour of farmers and credit lenders (Swinnen and Van Herck, 2011). In response, many farmers limit their inputs to avoid the risk of investment losses.

Land expansion on recently abandoned croplands in temperate European Russia can reduce the production shortfalls that are caused by droughts in southern European Russia. However, investments in rural development are imperative to counteract the infrastructural degradation and enormous rural depopulation in temperate European Russia (Ioffe et al., 2004). Such investments are urgent because the environmental and economic costs of recultivating idle croplands increase with the time since abandonment, and every additional year of successional vegetation will render recultivation more costly in terms of recultivation efforts and carbon emissions.

Our time-discriminating approach to evaluate the production potentials for cropland accounts for the carbon emissions that are incurred by land-use change. However, we did not consider other greenhouse gas emissions that are associated with intensifying production, such as emissions of fertilization and higher energy use from producing inputs and mechanization (Matson et al., 1998; Snyder et al., 2009). Moreover, we disregarded institutional and socio-economic factors (e.g., land market, labour supply and accessibility) that may constrain the re-use of abandoned cropland (Deininger et al., 2011; Lambin et al., 2013). Finally, we simulated yield potentials with observed recent weather conditions, but the yield potential will be influenced by future climate conditions. The projected climate change suggests increases in the drought frequency and thus more frequent production shortfalls, particularly in the southern breadbaskets (Alcamo et al., 2007). Initiatives to adapt crop production to climate change are therefore critical and should include both agronomic (e.g., irrigation, increasing water productivity, minimum tillage and rotations) and genotypic (development of drought-tolerant varieties) improvements (Turner and Asseng, 2005; Faramarzi et al., 2009; Challinor et al., 2014).

Acknowledgements

This manuscript benefited from the valuable contributions of Friedrich Koch, four anonymous reviewers, and Martin van Ittersum. We are grateful for the financial support of the Leibniz Association's “Pakt für Forschung”, the German Federal Ministry of Education and Research (BMBF) (Code01 LL0901A), and the German Federal Ministry of Food and Agriculture (BMEL) (GERUKA).

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