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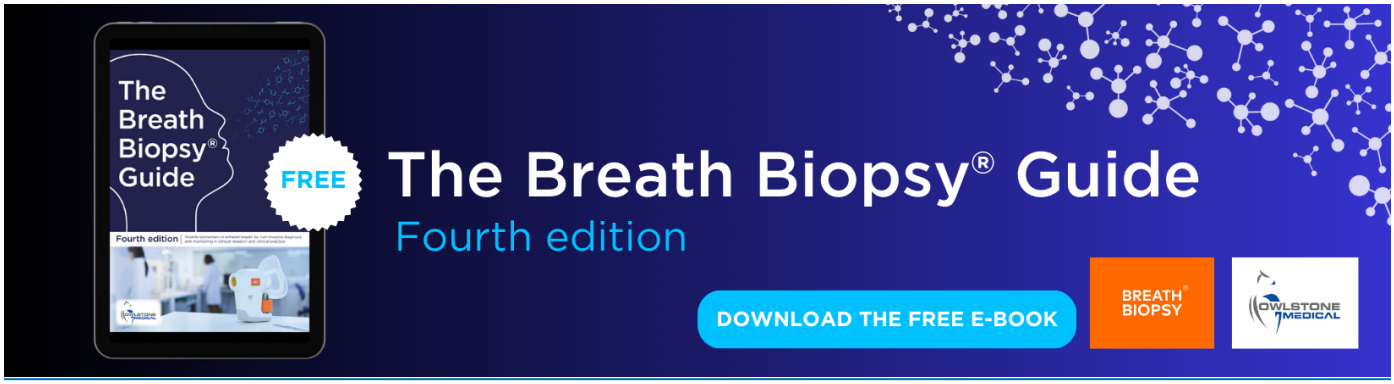

Environmental Research Letters

LETTER

# Increasing crop production in Russia and Ukraine—regional and global impacts from intensification and recultivation

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## Abstract

Russia and Ukraine are countries with relatively large untapped agricultural potentials, both in terms of abandoned agricultural land and substantial yield gaps. Here we present a comprehensive assessment of Russian and Ukrainian crop production potentials and we analyze possible impacts of their future utilization, on a regional as well as global scale. To this end, the total amount of available abandoned land and potential yields in Russia and Ukraine are estimated and explicitly implemented in an economic agricultural sector model. We find that cereal (barley, corn, and wheat) production in Russia and Ukraine could increase by up to 64% in 2030 to 267 million tons, compared to a baseline scenario. Oilseeds (rapeseed, soybean, and sunflower) production could increase by 84% to 50 million tons, respectively. In comparison to the baseline, common net exports of Ukraine and Russia could increase by up to 86.3 million tons of cereals and 18.9 million tons of oilseeds in 2030, representing 4% and 3.6% of the global production of these crops, respectively. Furthermore, we find that production potentials due to intensification are ten times larger than potentials due to recultivation of abandoned land. Consequently, we also find stronger impacts from intensification at the global scale. A utilization of crop production potentials in Russia and Ukraine could globally save up to 21 million hectares of cropland and reduce average global crop prices by more than 3%.

## 1. Introduction

Global population and consumption levels, and consequently global food demand, are expected to increase substantially in the coming decades (Godfray *et al* 2010, Tilman *et al* 2011). Furthermore, the recent striving of many countries towards a transformation to 'bio-based economies' indicates a growing competition for biomass for food, feed, fiber and fuel production purposes (Lewandowski 2015).

These prospects have caused a discussion about how additional agricultural production can sustainably be facilitated. The utilization of idle agricultural potentials is one identified option. On the one hand, agricultural production may be intensified, since many regions face large yield gaps between biophysically attainable and current yields (Godfray *et al* 2010, Mueller *et al* 2012, GYGA 2017). On the other hand, some potentially available cropland with low environmental or social trade-offs could be taken into production (Lambin *et al* 2013).

Russia and Ukraine are countries with relatively large untapped agricultural potentials, both in terms of abandoned agricultural land and existing yield

gaps (Schierhorn *et al* 2014a, Ryabchenko and Nonhebel 2016). After the collapse of the Soviet Union, during the 1990s, the agricultural sectors of former Soviet countries were suddenly faced with increasing international competition, while at the same time input- and output-subsides were drastically reduced (Nefedova 2011, Lerman *et al* 2004). The rural population increasingly left the countryside (Ioffe *et al* 2004, Prishchepov *et al* 2013), fertilizer consumption dropped significantly (Schaffartzik *et al* 2014, Swinnen *et al* 2017) and agricultural productivity and output declined (Bokusheva *et al* 2012). The livestock sector was particularly affected and an enormous decline in livestock production resulted in diminishing demand for animal feed (Liefert *et al* 2013). These developments led to strong declines in land use and average yields in the first years of transition.

Despite recent recultivation trends, vast amounts of abandoned cropland are still frequently reported (Meyfroidt *et al* 2016, Smaliychuk *et al* 2016, Schierhorn *et al* 2013). Also yields increased again during the 2000s. Yet, yield gaps in Russia and Ukraine remain significant, mainly due to limitations in nutrient and water application (Schierhorn *et al* 2014b, Mueller *et al* 2012).

Low input application rates reflect the high volatility of returns in agriculture, which—in combination with insufficient insurance systems—incentivize producers in Russia and Ukraine to limit inputs to avoid financial losses (Bobojonov *et al* 2014, Schierhorn *et al* 2014a). In the past, the Russian and Ukrainian governments additionally increased the price risk by imposing temporary export restriction as a response to harvest failure to protect domestic consumers in the short run (Fellmann *et al* 2014).

Furthermore, higher investments in the physical infrastructure, particularly in storing and transportation capacities, but also in modernization of farm equipment, are required to facilitate a substantial increase of agricultural production in Russia and Ukraine (Liefert *et al* 2013, Smaliychuk *et al* 2016). However, existing credit institutions limit capital availability, and the absence of functioning land markets and property right protection hampers private investments (Lioubimtseva and Henebry 2012, Nizalov *et al* 2015). Last but not least, the shortage of skilled workers in the agricultural sector is a major challenge (Liefert and Liefert 2012). In summary, a substantial increase of production quantities would likely require major institutional changes.

In the literature, several studies quantify either existing yield gaps on already cultivated croplands (Mueller *et al* 2012, Schierhorn *et al* 2014b, GYGA 2017) or the amount of available idle agricultural land suited for potential recultivation in the region (Lambin *et al* 2013, Schierhorn *et al* 2013, Smaliychuk *et al* 2016), but only a few studies quantify production potentials of both. For instance, Schaffartzik *et al* (2014) provide an analysis of production potentials of rapeseed-based biofuels in Ukraine and Swinnen *et al* (2017) analyze wheat production potentials in Russia, Ukraine and Kazakhstan. Schierhorn *et al* (2014a) calculate production potentials for wheat in European Russia. They estimate that due to a combination of recultivation and increasing yields, wheat production could be increased by up to 32 Mt (million tons) under rain fed conditions. For Ukraine, Ryabchenko and Nonhebel (2016) calculate that in the short term, wheat production could be increased by 8.4 Mt by taking land and yield potentials into account. Together, the estimated possible additional wheat production from unused potentials represents roughly 6% of the average global annual wheat production of the period 2010–2014 (FAO 2016). These figures exemplify the significance of the untapped agricultural potentials in Russia and Ukraine—for the region itself as well as for international markets.

In the reviewed studies, however, market effects from competition with other commodities or production in other regions were not taken into account. We extend existing literature by presenting a comprehensive assessment of Russian and Ukrainian crop production potentials, taking abandoned land and almost the full set of relevant crops (wheat, barley, corn, rapeseed, sunflower, soybeans, and potato) into account. Furthermore, we analyse the impacts a future utilization of these potentials could have on global crop prices and land use, since an increasing Ukrainian and Russian crop production will likely increase exports and thus, impact production, land use and food prices elsewhere (Hertel *et al* 2014).

To this end, we analyze different scenarios about recultivation and intensification in Russian and Ukrainian agriculture. In a first step (section 2), we provide a map of abandoned land in the region, as well as yield potentials for seven different crops currently covering 80% of the harvested area in Russia and 90% in Ukraine. The resulting spatially explicit datasets are combined with data on production costs and introduced into a global agricultural sector model (for a flow chart of the methodology see SI appendix, section 5). Subsequently, different future scenarios on the utilization of crop production potentials are specified (section 3). The underlying idea is to simulate a removal of institutional and investment obstacles. Based on these scenarios, we then analyze regional and global market effects and impacts on land use change (section 4).

## 2. Data and models

### 2.1. Abandoned land

A hybrid abandoned land map at a 300 m resolution for circa 2008–2012 was developed by application of a Bayesian approach to integrate different sources of information. These include land cover maps from different years, cropland maps, abandoned

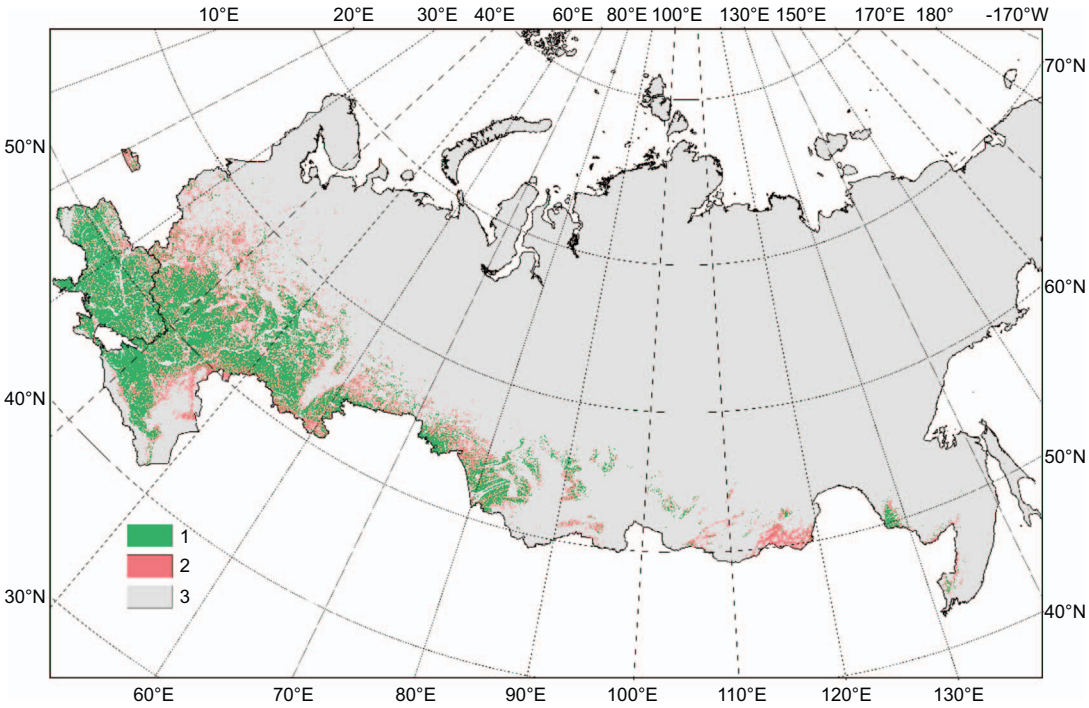


**Figure 1.** A hybrid abandoned agricultural land map. Legend: (1) active cropland; (2) abandoned agricultural land; (3) other land cover/land use types.

agricultural land maps, statistical datasets and a reference dataset on cropland and abandoned land that has been collected via the Geo-Wiki online platform (https://geo-wiki.org/) with the help of regional experts, who have visually interpreted high-resolution Bing maps and historical imagery in Google Earth. The final map differentiates between thematic classes 'active cropland', 'abandoned agricultural land' and 'other land cover/land use types' (see figure 1). The abandoned agricultural land is defined as land that has been under production in 1990 and was abandoned for more than five years afterwards. Land that has been cultivated during the period from 2008–2012 is defined as cropland.

The map has been calibrated with the statistics on abandoned areas at province level, which we calculated as the difference between the arable and cultivated area (FACRE'RF 2011, State Statistics Service of Ukraine 2013). In total 31.2 Mha (million hectares) of abandoned land are identified in Russia and 2.6 Mha in the Ukraine, respectively. However, it doesn't mean that the whole identified abandoned land is directly available for agricultural production. A detailed description of the methodology of creating and assessing the hybrid land cover map is provided in the SI appendix, section 1 available at stacks.iop.org/ERL/13/025008/mmedia.

### 2.2. Yield potentials

Biophysical crop yield potentials and their respective input requirements for major staple crops in Russia and the Ukraine were estimated with the global gridded crop model based on EPIC (Balkovič *et al* 2014, see SI appendix, section 2). A spatially explicit analysis was conducted to generate rain-fed (i.e. water-limited) yield potentials and irrigated yield potentials, accounting for different crop management practices and environmental conditions, including climate, soil, and terrain. We apply the concept of crop yield potential described by van Ittersum *et al* (2013). The yield potential reflects the yield simulated for a crop cultivar when water and nutrients are not limiting while other biotic stresses are not considered. The potentials are estimated for the climatic conditions of 2000–2010 assuming the present-day distribution of crops and no cultivar adaptations are considered. The EPIC-IIASA model was constructed and parameterized for crop management practices around the year 2000 (see input data summarized in SI appendix, table 1.

On the one hand, yield potential is a theoretical concept, and it has been observed that yields hardly exceed 80% of their estimated potential yields (Lobell *et al* 2009). On the other hand, experience shows that EPIC tends to underestimate yields at higher yield levels (Balkovič *et al* 2013, 2014) due to underrepresenting the high-performing cultivars in advanced agricultural systems. For the work at hand, we assume that both effects compensate each other and thus, we apply the estimated yield potentials directly, implicitly reflecting 80% levels of potential yields.

We compare our yield assumptions[2] to attainable yields as estimated by Mueller *et al* (2012) (figure 2).

[2] Shares of rain-fed and irrigated systems applied according to allocation in the GLOBIOM base year 2000, which are based on You and Wood (2006).

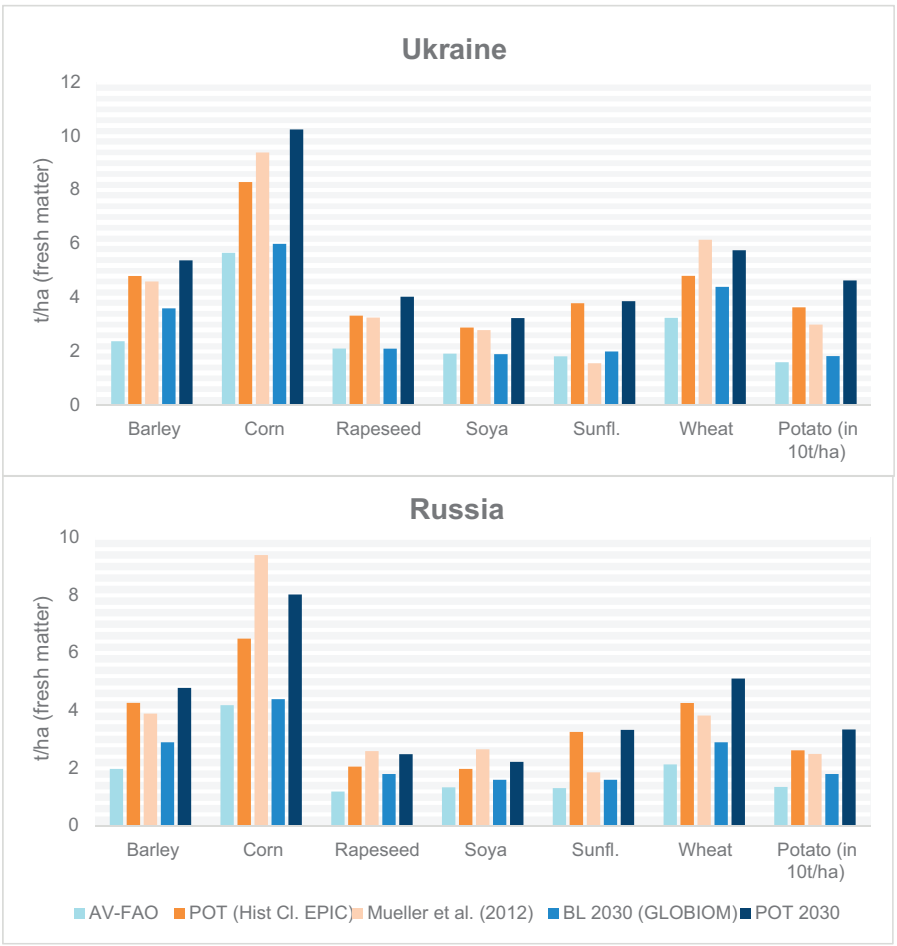


**Figure 2.** Yields and yield potentials (t ha$^{-1}$) for Ukraine and Russia; **AV-FAO**: Average of observed yields of the period 2010–2014; **POT (Hist Cl. EPIC):** average yield potentials based on EPIC figures under historical climate (compare 2.2); Mueller *et al* (2012): attainable average yields as presented in their publication; **BL2030:** GLOBIOM base year yields plus assumed exogenous growth trends as applied in the baseline until 2030; **POT2030:** EPIC yield potentials plus assumed increase in potentials until 2030, as applied in the YD_high scenario. For the calculation of POT (Hist), BL2030 and POT2030, spatially explicit yields are applied to the area distribution of the GLOBIOM base year.

Their estimates rely on the assumption that the highest yields observed in a region with a specific climate are a good proxy for the maximum attainable yield for all other regions with a similar climate. According to Lobell *et al* (2009), this methodology tends to underestimate yield potentials. In general, our yield potentials are similar to the attainable yields of Mueller *et al* (2012) except for maize and soybean yields in Russia, and soybean and wheat in Ukraine, which are underestimated compared to Mueller *et al* (2012). In addition, sunflower was overestimated in Ukraine. More detailed information is available in section 2 in the SI appendix. It should be noted that the simulated period of 2000–2010 differs from that used by Mueller *et al* (2012) in their analysis, which makes the comparison less straightforward.

### 2.3. Market model

The generated datasets on abandoned land and yield potentials are integrated into the Global Biosphere Management Model (GLOBIOM, Havlík *et al* 2011, 2014). GLOBIOM is a global recursive dynamic bottom-up partial equilibrium model integrating the agricultural, bioenergy and forestry sectors. It is a linear programming model with a spatial equilibrium approach (Takayama and Judge 1971). An agricultural and forest market equilibrium is computed, based on a welfare maximizing objective function subject to resource, technology, demand and policy constraints. Model details are presented in SI appendix, section 3. Russia and Ukraine are represented as single regions in GLOBIOM, in addition to 30 other regions either representing large single countries or country aggregates.

We incorporated information about available abandoned land (as described above) into GLOBIOM as an own land use category, adding a new potential source of cropland and facilitating the simulation of better accessibility to abandoned land. A detailed description of the mechanism of land use change in GLOBIOM is presented in the SI appendix, section 3.3.

In compliance with the EPIC estimates, new 'high-input' production systems (irrigated and rain-fed) are implemented into GLOBIOM, implicitly reflecting 80% levels of potential yields. For this purpose, we combine yields and inputs with corresponding, spatially explicit production costs. The production costs

for the new high-input production systems have been provided by the IIASA AgriCostModel (ACM, compare SI appendix, section 4). ACM calculates production costs for different crops and management systems at the spatial resolution level of the GLOBIOM model.

High-input production systems are defined for wheat, barley, corn, rapeseed, sunflower, soybeans, and potato production, which together represent 80% of the area harvested in Russia and 90% in Ukraine, respectively (FAO 2016). Average yields and costs structures of the defined high-input production systems, as well as the current production systems, can be found in the SI appendix, section 4.3.

## 3. Scenario description, assumptions, and quantification

With the described model and model extensions, we analyze several scenarios, reflecting different investment and institutional development efforts. These scenarios are compared to a reference scenario which reflects future developments without these additional efforts, the so-called baseline. For the baseline scenario, we refer to the Shared Socio-economic Pathway 2 (SSP2) which is a middle-of-the-road scenario (O'Neill *et al* 2014) and often is considered as a business-as-usual scenario (more details can be found in SI appendix, section 3.4).

We assume that an improved institutional environment and increased public and private investments in the agricultural sectors of Ukraine and Russia would result in better accessibility of farmers to abandoned cropland and would ease a shift in production structure towards high-input production systems for crops. To analyze the impacts of such developments, we run several scenarios simulating better access to abandoned cropland and high-input systems and combinations of them. Scenario details are presented in the following paragraphs. It shall be emphasized that our scenarios reflect long-term developments and thus, do not include current political issues such as the Russian import ban.

### 3.1. Recultivation of abandoned land

Abandoned cropland refers to land that has already been under production in Soviet times, and at least parts of it can potentially be taken back into production. However, it is clear that several constraints for the uptake of abandoned land exist and that recultivation of some land can be associated with high environmental trade-offs in terms of carbon release or biodiversity losses (Meyfroidt *et al* 2016, Kurganova *et al* 2015, Schierhorn *et al* 2013).

Thus, we specify two scenarios with different levels of recultivation attempts of abandoned land. For the definition of a more conservative scenario ('CONS') that sets a relatively small share of the abandoned land as de facto available, we refer to Meyfroidt *et al* (2016). In their paper, they categorize abandoned cropland in Russia and Ukraine according to the strengths of different constraints (socioeconomic, accessibility, agro-environmental) and also define land that is connected to high environmental trade-offs. Out of 31.4 Mha total abandoned land in Russia and 2.6 Mha in the Ukraine, they specify 5.3 Mha and 0.9 Mha, respectively, as potentially available cropland with no strong trade-offs, low socioeconomic and accessibility constraints and favorable agro-environmental conditions. We calibrate the GLOBIOM model to recultivate the amount of potentially available cropland as identified by Meyfroidt *et al* by 2030. When land is recultivated, the assumption is that productivity is the same as in the already existing neighboring cropland, which may lead to an overestimation of productivity of recultivated land since less fertile lands were likely abandoned first (Prishchepov *et al* 2013). However, other reasons such as poor accessibility or labor shortage could have led to abandonment as well, which don't necessarily imply lower productivity.

For the more advanced scenario ('ADV'), we assume a higher rate of recultivated abandoned land until 2030 and calibrate the land-conversion function of the model accordingly. In Russia 9.5 out of 31.2 Mha are assumed to be recultivated and for the Ukraine 1.6 out of 2.6 Mha. These figures are higher than the potentially available cropland as identified in the 'CONS' scenario, with the underlying assumption that some of the restraining constraints are being removed. Other studies estimate similar amounts of abandoned land with few constraints and no significant trade-offs for Russia (Lambin *et al* (2013): 8.7 Mha; Schierhorn *et al* (2014a): 9.5 Mha).

### 3.2. Increasing yields due to high-input system application

The new high-input production systems (as developed in section 2.2) are activated to run investment scenarios until 2030. This means that the model can choose between the standard production systems from the baseline and the newly implemented high-input production systems for each grid cell, depending on the cost-effectiveness of the system. The expansion of irrigated high-input systems is restricted to areas where already irrigated production systems exist in the base year.

We analyze scenarios with two different intensification settings. In the first setting, the high-input production systems as described in 2.2 are implemented into the model (scenario 'high'). In the second setting, production systems are implemented closing only 50% of the yield gap between the actual yields and the yields as defined for the high-input production systems (scenario 'medium'). The 'medium' production systems are based on linear interpolation between 'baseline' and 'high' systems.

Since we run scenarios up to the year 2030, some assumptions need to be made on the developments

**Table 1.** Scenario combinations. YD (Yield) refers to the assumptions on intensification, LD (Land) is used, when scenario assumptions only directly affect land use. Detailed scenario descriptions are presented in 3.1 and 3.2.

| | | Recultivation options | | |
|---|---|---|---|---|
| | | current | conservative (CONS) | advanced (ADV) |
| Intensification scenarios | high | YD_high | YD_high_CONS | YD_high_ADV |
| | medium | YD_med | YD_med_CONS | YD_med_ADV |
| | current | Baseline | LD_CONS | LD_ADV |

of yields over time. For our baseline scenario, exogenous yield growth shifters are applied, which are based on estimated yield response functions to GDP per capita for different income groups of countries (SI appendix, section 3.4). These shifters represent a mixture of partly closing yield gaps and increasing yield potentials over time. Thus, exogenous growth shifters for our estimated high-input production systems need to be adjusted to reflect that they only represent the increase that is coming from research and development. To this end, we assume that potential yields in Russia and Ukraine increase with the same rate that is applied for western European countries[3] in our baseline. The underlying assumption is that in western Europe, nutrient-limitations have already been closed to a large extent and hence, estimated shifters capture the increase of yield potentials by research and development. Resulting potential yields for the year 2030 are presented in figure 2.

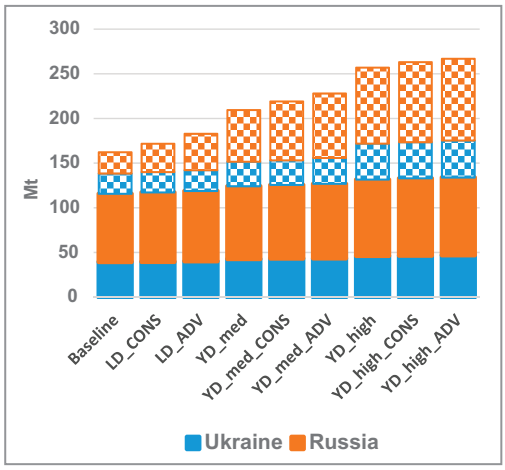


**Figure 3.** Cereals (barley, corn, wheat) production and net-trade in 2030; Overall bar: total production; plain area: domestic consumption (human consumption, feed, seed, and processing); patterned area: net-exports.

### 3.3. Scenario combinations

It is likely that institutional development and higher public investments in the agricultural sector would affect both, land-use change and production system changes, at the same time. Thus, we combine our recultivation options and high-inputs production systems as presented in table 1, with the baseline being the reference scenario with no additional recultivation attempts and no implementation of high-input production systems.

## 4. Results

### 4.1. Production and trade in Russia and Ukraine

Scenario results for production and trade of cereals (barley, corn, and wheat; figure 3) suggest that the impact from intensification on the existing cropland is larger than the impact from recultivation of abandoned land. This effect can be observed for both countries but is more distinct in Ukraine—mostly because land reserves are higher in Russia than in Ukraine.

All scenarios have in common that large shares of the additional production translate into net exports. Domestic consumption (including human consumption, feed demand, processing demand, seed demand) shows only little response. In our scenarios, we do not change assumption on livestock productivity compared to the baseline. With an increasing productivity in the livestock sector, however, it is likely that more feed demand arises within Russia and Ukraine, which in turn could increase domestic demand for crops and impact international livestock markets.

For the scenario with the strongest impact (YD_high_ADV), the full provision of the defined high-input systems and relatively easy access to abandoned land for recultivation is assumed. In this scenario, cereal production in 2030 in Russia and Ukraine increases to 267 Mt (million tons) from 162 Mt in the baseline, which reflects a 64% increase. The domestic consumption increases by less than 16% of baseline levels, but net-export figures almost triple. In comparison to the baseline, net exports of Ukraine and Russia increase by 86.3 Mt of barley, corn, and wheat, which represent 4% of the global production of these crops. A similar result also can be observed for oilseed production and trade (SI, section 6.1). In the YD_high_ADV scenario, common net-exports of sunflower seeds, rapeseeds, and soybeans increase by 18.9 Mt in 2030 compared to the baseline, representing 3.5% of global production of these crops in 2030.

In scenarios where intensification is provided as an option (i.e. in all YD_med and YD_high scenarios), high-input production systems are applied for all crops on at least 95% of the harvested area, except for potatoes where the share is around 60%. This may seem like an extreme step, however, when looking

[3] In the GLOBIOM set-up, the region 'Western Europe' consists of the countries Austria, Belgium, Luxembourg, France Germany and the Netherlands.

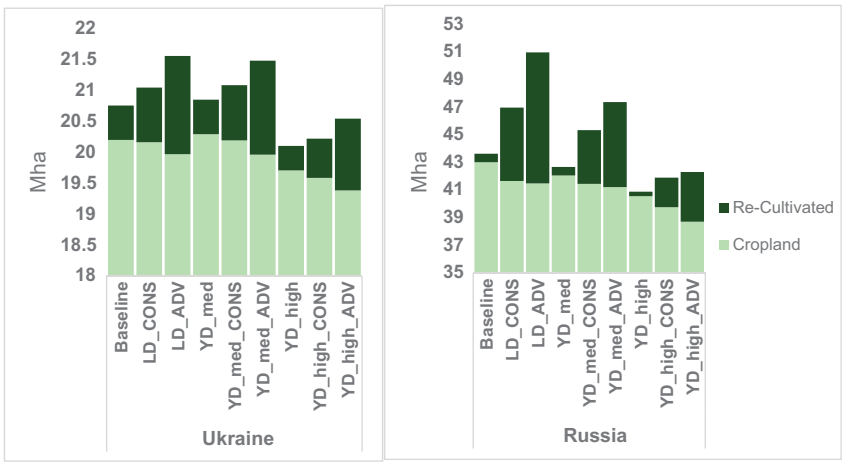


**Figure 4.** Cropland use in Ukraine and Russia in 2030. The overall bars indicate the total cropland use for different scenarios. The upper (dark green) part refers to abandoned land that has been recultivated since 2010 and is used as cropland in 2030. Note: bars are cut at 18 Mha in Ukraine and 35 Mha in Russia for better visualization of recultivation effects in the single scenarios.

at western European agriculture (Jepsen *et al* 2015), at least in the long run, it is not implausible.

With increasing intensification, we also observe some specialization effects. Russian cereal production increases by 70%, while Ukrainian cereal production increases by 39% in the strongest intensification scenario (YD_high). A reverse picture arises for oilseed production impacts where Russian production increases by 48% and the Ukrainian production more than doubles, in comparison to oilseed production in the baseline.

Sensitivity analysis of production costs of high-input systems revealed that, despite costs being an important driver, results were quite robust. Keeping the costs of the business-as-usual systems constant and varying the total cost difference between newly implemented high-input production systems and business-as-usual systems by up to 20%, generates an up to 5% decrease in cereal production (SI appendix, section 7.1).

### 4.2. Land use in Russia and Ukraine

The different scenarios lead to different developments of cropland use in Russia and Ukraine (figure 4). The amount of recultivated land in the scenarios LD_CONS and LD_ADV reflects the calibrated recultivation assumptions as described in section 3.1. For these two scenarios, we observe an increase in total cropland in comparison to the baseline, due to the better recultivation options. However, with increased production, prices decrease and production at some marginal areas is not profitable any longer. Thus, some marginal cropland that was under production in the baseline will be abandoned and substituted by recultivated abandoned land with better agricultural conditions. Similar land use patterns can be observed when analyzing the impacts of better recultivation options on scenarios with higher yield per hectare (i.e. YD_med_COSN and YD_med_ADV in comparison to YD_med; and YD_high_COSN and YD_high_ADV in comparison to YD_high).

In intensification scenarios, an overall land-saving effect is observed due to the introduction of high-input production systems. However, the land-saving effect in YD_med does only occur in Russia and is relatively small, while the additional impact from YD_med to YD_high is much stronger in both countries. The mechanism behind this result is, that increasing marginal trade costs are assumed. Thus, when yields increase only moderately (YD_med), most of the additional production will be exported. However, with a substantial increase of yields and respectively production in comparison to the baseline, marginal trade costs increase stronger and thus, additional production remains in the country, domestic commodity prices are going down, and less cropland is being used. Despite this land-saving effect, intensification, however, can be connected to substantially higher fertilizer application rates (SI appendix, chapter 6.2).

### 4.3. Global impacts

At the global scale, results are in line with the regional scale: in 2030, impacts from intensification are stronger than the impacts resulting from recultivation (figure 5). Yet, compared to regional impacts in Russia and Ukraine, globally observed land-use effects from intensification are even stronger. A cropland reduction of 0.87 Mha (3.4 Mha) in Russia and Ukraine for the YD_med (YD_high) scenario (compared to the baseline) translates globally into a reduction of 10.8 Mha (21.5 Mha) of cropland. This reflects that due to trade effects, marginal land with, on average, lower yields is set free from agricultural production in other regions. More than one quarter (26%) of the land that globally is saved in the YD_high scenario appears in former Soviet Union countries (including Russia and Ukraine), another 25% in Europe and 15% in Latin America. More details on the distribution of

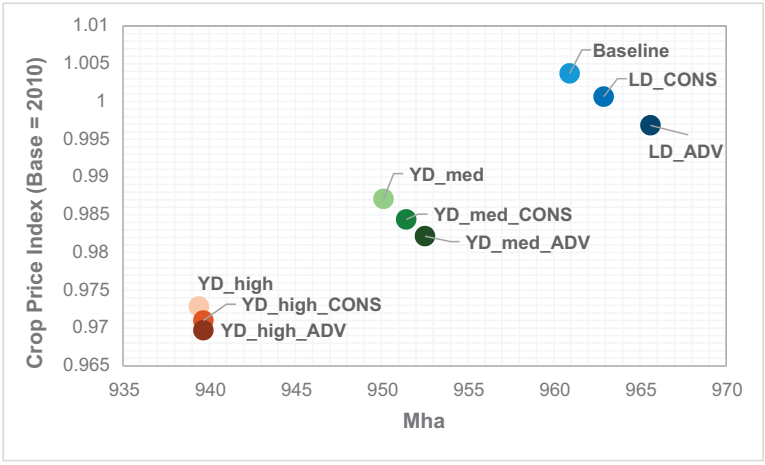


**Figure 5.** Global price and land use effects in 2030. The crop price index is a weighted average of all endogenously calculated crop prices. The index is set to 1 for the year 2010 (since scenarios are only specified for the years after 2010). Global cropland refers to the sum of cropland that is used for the production of endogenously represented crops in GLOBIOM.

land savings due to intensification can be found in the SI, section 6.3.

Global price impacts show as well that the strongest production gains arise in the intensification scenarios. Instead of a 0.4% increase in average crop prices compared to 2010, as shown for the baseline, the YD_high scenario leads to a price drop of 2.7%. The LD_ADV scenario, in contrast, leads to a price drop of only 0.3%.

Contrary to the intensification scenarios, better recultivation options in Russia and Ukraine without simultaneous intensification lead to an increasing land use at the global scale, since the additional land use in Russia and Ukraine in the LD_CONS and LD_ADV scenarios is stronger than land use reductions in the rest of the world.

With high intensification assumed in the background, the impact of recultivation on global land use is almost zero (i.e. YD_high_ADV and YD_high_CONS versus YD_high). Given the increasing land use in Russia and Ukraine, this means that for every additional hectare in this region almost one hectare cropland is saved elsewhere.

The amount of increased agricultural production and the respective impact on the global scale are not solely determined by existing agricultural potentials, but as well by the global demand for Russian and Ukrainian crops, and the resulting international price levels in the baseline (Saraykin *et al* 2017). Global demand projections in turn depend on many different factors, such as income development, population growth or trade relations. For all these factors, very diverse pathways can be projected (e.g. Dellink *et al* 2017, Kc and Lutz 2017). We, however, apply the ceteris paribus assumption and do not change these projections between our scenarios. Testing our scenarios against different projection for all drivers would be beyond the scope of this article. However, since it is not unlikely that institutional development may involve changes in trade relations, we carried out a sensitivity analysis to test the impacts of different trade specifications to reflect the uncertainty on the development.

### 4.4. Potentials and trade openness

Bilateral trade relations in GLOBIOM are represented by a linearized constant elasticity trade cost function if bilateral trade flows between two regions are observed in the base year and by a quadratic cost function if no trade flows are observed in the base year. When the elasticity is low, trade costs rise quickly with the increase in traded quantities while when the elasticity is high, trade costs rise at a slower pace. To reflect low trade costs and beneficial international trade relations, initial trade costs were reduced by 10%, trade cost elasticities were doubled, and the quadratic function was divided by 2. An opposite development of increasing trade costs and less beneficial trade relations are introduced by 10% higher initial trade cost, a reduction of trade cost elasticities by 50% and a multiplication by 2 of the quadratic cost function.

The analysis reveals the importance of trade options for the utilization of agricultural potentials in Russia and Ukraine (figure 6). Impacts are stronger on production values because in the scenarios production values already deviate stronger from the baseline than land use values. In the standard scenario with the strongest production impact as presented above (YD_high_ADV), cereal production in Russia increases by 78% and in Ukraine by 42% compared to baseline production. If trade relations improve and trade costs decrease with the better institutional environment and more investments, cereal production could increase by 98% in Russia and by 62% in Ukraine instead. On the other hand, if for some reason trade relations worsen and trade costs increase (compared to the baseline), cereal production in Russia and Ukraine may increase only by 46% and 14%, respectively.

At the global scale (SI appendix, section 7.2), changes in trade costs reveal a trade-off between price

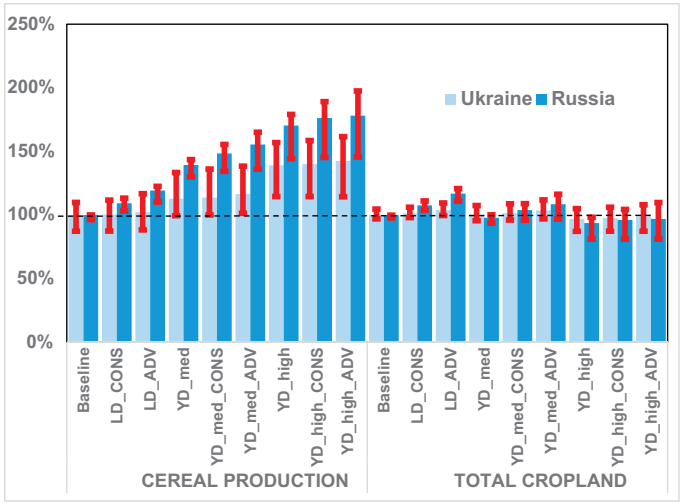


**Figure 6.** Sensitivity of cereal production and cropland use in Russia and Ukraine. Values in percent of Baseline 2030 results. The upper end of the red error bars indicates results from scenarios with low trade costs (ceteris paribus) and the lower end of the error bars show results from scenarios with higher trade costs (ceteris paribus).

and land use. With higher trade costs, less agricultural potentials are being used in Russia and Ukraine, resulting in lower global land use and higher global price levels. On the other hand, low trade costs lead to higher global land use but lower price levels.

## 5. Discussion and conclusion

We analyzed crop production potentials of Russia and Ukraine which could be uncovered with higher investments and institutional improvements. The novelty of our approach is its comprehensiveness (we take abandoned land and almost the full set of relevant crops into account) and the application of an agricultural sector model, which allows for an impact analysis at the reginal as well as at the global scale.

Our results show that substantial potentials in crop production do exist in Russia and Ukraine and that large parts of the additional production can be exported to world markets. We find that cereal production (here: barley, corn, and wheat) in Russia and Ukraine could increase up to 267 Mt per year in 2030, representing a 64% increase compared to the baseline production of 162 Mt. Additional net exports of Ukraine and Russia comprise up to 86.3 Mt, which would represent 4% of global production of these crops. A similar result can be observed for oilseed production and trade (here: rapeseed, soybean, and sunflower). Net-exports could increase by up to 18.9 Mt in 2030, representing 3.5% of global production in 2030.

These results, however, reflect that in our scenarios no exogenous changes in livestock production capacities or productivity would take place in Russia and Ukraine compared to the baseline. With an increased livestock production, it is likely that a larger share of crops would be used as animal feed instead of being exported. This is not unlikely to happen, especially since recently more subsidies are directed to the livestock sectors in the region (Liefert and Liefert 2012).

Our analysis reveals that production potentials due to intensification are higher than potentials due to recultivation of abandoned land. In our strongest scenario, which combines recultivation of abandoned land with an intensification of crop production, 8% of the additional cereal and oilseed production in Ukraine are coming from recultivation of abandoned land while 92% are coming from intensification of production on already utilized cropland. These findings correspond with findings in Ryabchenko and Nonhebel (2016), who estimate that 10% of the untapped production potentials for wheat in Ukraine would be connected to land expansion while 90% of the potentials would be connected to intensification. Results for European Russia in Schierhorn *et al* (2014a) suggest that a somewhat higher share of 21% of the untapped wheat production potentials could be gained from recultivation and 79% from intensification[4]. In our study, some of the available abandoned land in Russia is not recultivated when intensification is assumed because it is not profitable with declining commodity prices. Thus, for Russia, we estimate that only 9% of additional production is due to recultivation and 91% due to intensification, with some of the available abandoned land not being recultivated.

On international markets, we consequently find stronger impacts of intensification. However, both intensification and recultivation in Russia and Ukraine would lead to decreasing crop prices and reduced land use in other parts of the world outside Russia and Ukraine. We find that the utilization of crop production potentials in Russia and Ukraine could globally

[4] Own calculations based on Schierhorn *et al* (2014a) results for a full yield gap closure scenario under rain-fed conditions and a recultivation of 4.4 Mha cropland.

save up to 21 Mha of cropland and at the same time reduce average crop prices by more than 3%. Results show that at the global level more production is provided at lower prices, which is an important finding from a food security perspective.

We also show that the level of utilization of agricultural potentials heavily depends on existing trade options by carrying out a sensitivity analysis of trade costs assumptions. This needs to be kept in mind when interpreting the results of our paper.

Globally, changes in trade costs reveal a trade-off between crop price impacts and land use. Higher trade costs lead to lower production levels in Russia and Ukraine, globally (including Russia and Ukraine) to lower cropland utilization and higher international prices. Opposite effects appear with lower trade costs.

Intensification of agricultural production, on the one hand, has land saving effects at the global scale. On the other hand, it can lead to adverse environmental impacts at the local, regional, and even global level (Matson *et al* 1997). With intensified production in Russia and Ukraine, fertilization or pesticide application rates will substantially increase in the region but decline elsewhere. Global application rates rise slightly in our intensification scenarios. The overall environmental impact of intensification, however, depends on further factors, such as a country's environmental legislation or farmers' management skills. We do not explicitly take into account changes of net fertilization demand that may arise from changes in farm management practices. With this regard, an increase in nitrogen use efficiency may be an important parameter (Reis *et al* 2016). Furthermore, depending on the development of the Russian and Ukrainian livestock sectors, additional positive environmental impacts might be generated, taking Russia's large beef imports from Brazil and related land-use change developments in tropical regions into account (Schierhorn *et al* 2016).

In the presented intensification scenarios, high uptake rates of high-input production systems are observed. For most crops, more than 95% of the harvested area is under intensive production. This may appear as an extreme switch, particularly given the time frame of our analysis until 2030. It may seem relatively unlikely that all relevant institutional problems relating to the Russian and Ukrainian agricultural sectors, as described in the introduction, can be solved until then. In the medium to long run, however, a high share of intensive production systems may not be implausible, particularly when comparing to the intensification level of western European agriculture (Jepsen *et al* 2015). Similarly, our intensification scenarios imply relatively high annual rates of yield increase for some crops, which rarely have been observed in the past (Grassini *et al* 2013) and thus, represent an optimistic development. Nevertheless, the scope and direction of potential developments are plausible and indicate tendencies towards which Russia and Ukraine may be heading in the future.

In the paper at hand, different large-scale models have been applied, which requires many assumptions and thus, comprises uncertainties. We addressed uncertainties related to assumptions on trade and the cost structure of high-input production systems by sensitivity analysis with the GLOBIOM model. However, the presented global scenarios additionally depend on projections for population developments, income growth, consumer behavior, and technical progress, which we do not change between the scenarios. Conducting sensitivity analysis on all of these parameters would be beyond the scope of this article, but it should be kept in mind that the utilization of agricultural potentials in Russia and Ukraine is also influenced by these factors.

Furthermore, there are some caveats concerning the biophysical EPIC modelling, especially with respect to insufficiently captured heterogeneity in crop management practices, including distribution of crop varieties, cultivation practices, fertilization and irrigation allocation to individual crops (Balkovič *et al* 2013), insufficiently captured soil heterogeneity (Folberth *et al* 2016), uncertainty of crop yield aggregations (Porwollik *et al* 2016), and limited relevance at small scales (van Ittersum *et al* 2013). Owing to granularity in input data, our estimates of potential yields may not take into account the best-performing crop varieties under the given climate and soil conditions, leading to underestimation of crop yields obtained in high-productive agricultural systems. In the paper, we try to account for this by interpreting yield potentials as implicitly reflecting 80% levels of the potentials, which is a threshold that hardly is exceeded in reality (Lobell *et al* 2009). A comparison with attainable yields estimated by Mueller *et al* (2012) reveals similar values for most crops. However, our yield for maize and soybean in Russia, and soybean and wheat in Ukraine are lower, while sunflower values are higher, which may be owing to the described caveats.

Also, production potentials might increase more if irrigation is extended. In our analysis, we restrict irrigation expansion to zones where it has been in place in the base year. This, however, may not be unrealistic given the fact that water availability is limited and future climate change may even increase water stress (Alcamo *et al* 2007).

Climate change impacts are not explicitly considered in our paper. However, they may affect agricultural production potentials in the future. Impacts of climate change are predicted to vary across Russia and Ukraine. The northern parts may benefit from higher temperatures and longer growing seasons, yet, yield increases are expected to be rather moderate due to limited soil quality in this area. The southern parts where most of the crop production traditionally is taking place may be adversely affected by increasing climate variability (Swinnen *et al* 2017, Lioubimtseva and Henebry 2012).

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## References

Alcamo J, Dronin N, Endejan M, Golubev G and Kirilenko A 2007 A new assessment of climate change impacts on food production shortfalls and water availability in Russia *Glob. Environ. Change* **17** 429–44

Balkovič J, van der Velde M, Schmid E, Skalský R, Khabarov N, Obersteiner M, Stürmer B and Xiong W 2013 Pan-European crop modelling with EPIC: implementation, up-scaling and regional crop yield validation *Agric. Syst.* **120** 61–75

Balkovič J, van der Velde M, Skalský R, Xiong W, Folberth C H, Khabarov N, Smirnov A, Mueller N D and Obersteiner M 2014 Global wheat production potentials and management flexibility under the representative concentration pathways *Glob. Planet. Change* **122** 107

Bobojonov I, Götz L and Glauben T 2014 How well does the crop insurance market function in Russia? *International Congress of the European Association of Agricultural Economists* (Ljubljana)

Bokusheva R, Hockmann H and Kumbhakar S C 2012 Dynamics of productivity and technical efficiency in Russian agriculture *Eur. Rev. Agric. Econ.* **39** 611–37

Dellink R, Chateau J, Lanzi E and Magné B 2017 Long-term economic growth projections in the Shared Socioeconomic Pathways *Glob. Environ. Change* **42** 200–14

FACRE'RF 2011 State (national) report about the state and use of lands of Russian Federation in 2010 *Federal Agency of Real Estate Cadastre Report* (Moscow: Federal Agency of Real Estate)

FAOSTAT data 2016 Food and Agriculture Organization of the United Nations (http://faostat.fao.org/) (Accessed: 13 September 2016)

Fellmann T, Hélaine S and Nekhay O 2014 Harvest failures, temporary export restrictions and global food security: the example of limited grain exports from Russia, Ukraine and Kazakhstan *Food Sec.* **6** 727–42

Folberth C, Skalský R, Moltchanova E, Balkovič J, Azevedo L B, Obersteiner M and van der Velde M 2016 Uncertainty in soil data can outweigh climate impact signals in global crop yield simulations *Nat. Commun.* **7** 11872

Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M and Toulmin C 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–8

Grassini P, Eskridge K M and Cassman K G 2013 Distinguishing between yield advances and yield plateaus in historical crop production trends *Nat. Commun.* **4** 2918

GYGA 2017 Global Yield Gap Atlas (www.yieldgap.org) (Accessed: 17 October 2017)

Havlík P *et al* 2011 Global land-use implications of first and second generation biofuel targets *Energy Policy* **39** 5690–702

Havlík P *et al* 2014 Climate change mitigation through livestock system transitions *Proc. Natl Acad. Sci.* **111** 3709–14

Hertel T W, Ramankutty N and Baldos U L C 2014 Global market integration increases likelihood that a future African green revolution could increase crop land use and $CO_2$ emissions *Proc. Natl Acad. Sci.* **111** 13799–804

Ioffe G, Nefedova T and Zaslavsky I 2004 From spatial continuity to fragmentation: the case of Russian farming *Ann. Assoc. Am. Geogr.* **94** 913–43

Jepsen M R *et al* 2015 Transitions in European land-management regimes between 1800 and 2010 *Land Use Policy* **49** 53–64

Kc W and Lutz S 2017 The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100 *Glob. Environ. Change* **42** 181–92

Kurganova I, de Gerenyu V L and Kuzyakov Y 2015 Large-scale carbon sequestration in post-agrogenic ecosystems in Russia and Kazakhstan *Catena* **133** 461–6

Lambin E F, Gibbs H K, Ferreira L, Grau R, Mayaux P, Meyfroidt P, Morton D C, Rudel T K, Gasparri I and Munger J 2013 Estimating the world's potentially available cropland using a bottom-up approach *Glob. Environ. Change* **23** 892–901

Lerman Z, Csaki C and Feder G 2004 *Agriculture in Transition: Land Policies and Evolving Farm Structures in Post-Soviet Countries* (Oxford, New York: Lexington Books)

Lewandowski I 2015 Securing a sustainable biomass supply in a growing bioeconomy *Glob. Food Secur.* **6** 34–42

Liefert O, Liefert W and Luebehusen E 2013 Rising Grain Exports by the Former Soviet Union Region. USDA WHS-13A-01 (www.ers.usda.gov/publications/whs-wheat-outlook/whs-13a01.aspx) (Accessed: 18 March 2016)

Liefert W M and Liefert O 2012 Russian agriculture during transition: performance, global impact, and outlook *Appl. Econ. Perspect. Pol.* **34** 37–75

Lioubimtseva E and Henebry G M 2012 Grain production trends in Russia, Ukraine and Kazakhstan: new opportunities in an increasingly unstable world? *Front. Earth Sci.* **6** 157–66

Lobell D B, Cassman K G and Field C B 2009 Crop yield gaps: their importance, magnitudes, and causes *Ann. Rev. Environ. Resour.* **34** 179–204

Matson P A, Parton W J, Power A G and Swift M J 1997 Agricultural Intensification and Ecosystem Properties *Science* **277** 504–9

Meyfroidt P, Schierhorn F, Prishchepov A V, Müller D and Kuemmerle T 2016 Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan *Glob. Environ. Change* **37** 1–15

Mueller N D, Gerber J S, Johnston M, Ray D K, Ramankutty N and Foley J A 2012 Closing yield gaps through nutrient and water management *Nature* **490** 254–7

Nefedova T G 2011 Agricultural land in Russia and its dynamics *Reg. Res. Russ.* **1** 292–5

Nizalov D, Thornsbury S, Loveridge S, Woods M and Zadorozhna O 2015 Dynamics of agricultural production and land use in post-soviet Ukraine *Transition to Agricultural Market Economies: The Future of Kazakhstan, Russia and Ukraine* ed A Schmitz and W Meyers (Wallingford: Cabi International) pp 215–27

O'Neill B, Kriegler E, Riahi K, Ebi K, Hallegatte S, Carter T, Mathur R and Vuuren D 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400

Porwollik V *et al* 2016 Spatial and temporal uncertainty of crop yield aggregations Eur *J. Agron.* **88** 10–21

Prishchepov A V, Müller D, Dubinin M, Baumann M and Radeloff V C 2013 Determinants of agricultural land abandonment in post-Soviet European Russia *Land Use Policy* **30** 873–84

Reis S, Bekunda M, Howard C M, Karanja N, Winiwarter W, Yan X, Bleeker A and Sutton M A 2016 Synthesis and review: tackling the nitrogen management challenge: from global to local scales *Environ. Res. Lett.* **11** 120205

Ryabchenko O and Nonhebel S 2016 Assessing wheat production futures in the Ukraine *Outlook Agric.* **45** 165–72

Saraykin V, Yanbykh R and Uzun V 2017 Assessing the potential for russian grain exports: a special focus on the prospective cultivation of abandoned land *The Eurasian Wheat Belt and Food Security* ed S Gomez y Paloma, S Mary, S Langrell and P Ciaian (Cham: Springer) pp 155–75

Schaffartzik A, Plank C and Brad A 2014 Ukraine and the great biofuel potential? A political material flow analysis *Ecol. Econ.* **104** 12–21

Schierhorn F, Meyfroidt P, Kastner T, Kuemmerle T, Prishchepov A V and Müller D 2016 The dynamics of beef trade between Brazil and Russia and their environmental implications *Glob. Food Secur.* **11** 84–92

Schierhorn F, Müller D, Prishchepov A V, Faramarzi M and Balmann A 2014a The potential of Russia to increase its wheat production through cropland expansion and intensification *Glob. Food Secur.* **3** 133–41

Schierhorn F, Faramarzi M, Prishchepov A V, Koch F J and Müller D 2014b Quantifying yield gaps in wheat production in Russia *Environ. Res. Lett.* **9** 84017

Schierhorn F, Müller D, Beringer T, Prishchepov A V, Kuemmerle T and Balmann A 2013 Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus *Glob. Biogeochem. Cycles* **27** 1175–85

Smaliychuk A, Müller D, Prishchepov A V, Levers C, Kruhlov I and Kuemmerle T 2016 Recultivation of abandoned agricultural lands in Ukraine: patterns and drivers *Glob. Environ. Change* **38** 70–81

State Statistics Service of Ukraine 2013 Regions of Ukraine, Volume 2, Kyiv (www.ukrstat.gov.ua/druk/publicat/kat_u/2013/sb/12_13/zb_reg2_2013.zip)

Swinnen J, Burkitbayeva S, Schierhorn F, Prishchepov A V and Müller D 2017 Production potential in the bread baskets of eastern Europe and central Asia *Glob. Food Secur.* **14** 38–53

Takayama T and Judge G G 1971 *Spatial and Temporal Price and Allocation Models* (Amsterdam: North-Holland)

Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Nalt Acad. Sci.* **108** 20260–4

van Ittersum M K, Cassman K G, Grassini P, Wolf J, Tittonell P and Hochman Z 2013 Yield gap analysis with local to global relevance—A review *Field Crop. Res.* **143** 4–17

You L and Wood S 2006 An entropy approach to spatial disaggregation of agricultural production *Agric. Syst.* **90** 329–47