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Impact of Climate Change on Wheat Production in Ukraine

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About the Project "German-Ukrainian Agricultural Policy Dialogue" (APD)

The project German-Ukrainian Agricultural Policy Dialogue (APD) started 2006 and is funded up to 2018 by the Federal Ministry of Food and Agriculture of Germany (BMEL). On behalf of BMEL, it is carried out by the mandatary, GFA Consulting Group GmbH, and a working group consisting of IAK AGRAR CONSULTING GmbH (IAK), Leibniz-Institut für Agrarentwicklung in Transformationsökonomien (IAMO) and AFC Consultants International GmbH. Project executing organization is the Institute of Economic Research and Policy Consulting in Kyiv. The APD cooperates with the BVVG Bodenverwertungs- und -verwaltungs GmbH on the implementation of key components related to the development of an effective and transparent land administration system in Ukraine. Beneficiary of the project is the Ministry of Agrarian Policy and Food of Ukraine.

In accordance with the principles of market economy and public regulation, taking into account the potentials, arising from the EU-Ukraine Association Agreement, the project aims at supporting Ukraine in the development of sustainable agriculture, efficient processing industries and enhancing its competitiveness on the world market. With regard to the above purpose, mainly German, but also East German and international, especially EU experience are provided by APD when designing the agricultural policy framework and establishing of relevant institutions in the agriculture sector of Ukraine.

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EXECUTIVE SUMMARY

Climate change endangers future crop production through alterations in temperatures, changing precipitation patterns, and more frequent extreme weather events. It is therefore urgent to understand the potential effects that changing weather parameters may have on crop yields in order to adapt to climate change. Ukraine is particularly interesting in that respect because the country is an important player on the global grain market thanks to its large tracts of suitable agricultural lands. Historic climate data already point to increasing temperatures in Ukraine and climate forecasts suggest further warming, particularly in Southern Ukraine. We used a statistical approach to analyze associations between reported yields of winter wheat from country-wide data of 13,000 commercial farms and time series of historic weather data. The statistical relationships between historic yields and weather were used to predict the yield responses of winter wheat for two scenarios of future climate change. Under the modest climate change scenario, the results suggest limited effects on future wheat yields. However, the higher emissions scenario, which, at present, is close to the business-as-usual pathway, may substantially decrease wheat yields, particularly in the southern Steppe zone. Conversely, rising temperatures and increasing precipitation may slightly extend the growing period and result in modest yield increases in less fertile areas in northern Ukraine. To secure future crop production in view of climate change, more investments into regionally targeted adaptation strategies are warranted, such as into improvement of agronomic management strategies and developing drought-resistant plant material.

1. INTRODUCTION

Agricultural production crucially depends on weather conditions for plant growth. As a result, agriculture is sensitive to long-term trends and changes in climatic conditions (Nelson et al. 2014). Quantifying the relationships between short–term weather input data and crop yields is therefore essential for better understanding and forecasting responses of plant growth to long-term changes in weather conditions and for formulating timely adaptation measures and responses to climate change (Porter et al. 2014, Lobell and Burke 2010). However, the relationships between weather conditions and crop growth vary substantially, depending on biophysical site conditions, agricultural management, and technology available to farmers. Better understanding the relationships between weather inputs and crop output at fine spatial scale can help to inform farmers, investors, and policy makers in formulating adaptation strategies and interventions that make best use of current and future weather conditions.

Long-term changes in average weather conditions are expected under global climate change. While the projected climate changes may cause positive effects for crop production in some regions of the globe, negative effects are likely to prevail (Lobell et al. 2011). As future climate conditions are highly uncertain because of unknown future emissions pathways and because of the high complexity of simulating climatic conditions in the future, anticipating the potential linkages between future climate and future crop yields will necessitate assessing alternative future emissions scenarios in order to account for these uncertainties.

Climate change affects crop yields in manifold ways through changes in amounts, distribution, and extremes of precipitation and temperature (Schlenker and Roberts 2009, Ram 2016). The potential yield of a crop is determined by incoming solar radiation (Long et al. 2006). However, crop yields typically are lower than potential yields because various abiotic and biotic stress factors compromise plant photosynthesis and thus limit crop growth (Lobell et al. 2013, Asseng et al. 2014). The most important abiotic stress factors are temperature stress and water stress. For example, abnormal events, such as temperatures below zero in fall or extreme heat in spring, can cause substantial losses in wheat yields (Tack et al. 2015). Also globally, extreme heat events have been shown to result in significant production shortfalls in cereal yields (Lesk et al. 2016), and there is strong evidence that the frequency of extreme events will increase in many world regions (Porter et al. 2014). In sum, a large number of parameters related to temperature and precipitation affect crop growth, including their distribution during the growing period, interactions between temperature and precipitation, as well as extreme events.

Adaptation to climate change will be crucial to reduce climate-induced risks in regions where agricultural production reacts sensitive to the effects of climatic changes. At the farm level, adaption actions need to occur through changes in production practices that can better cope with the changing climatic conditions. For example, farmers can switch to crops with lower water demands or higher heat resistance, adapt sowing dates of crops, and adjust the timing and quantity of input applications (Howden et al. 2007). The tasks of policy makers are then to support farmers in adaptation, among others, through providing them with information platforms that elucidate potential changes and their likelihood of occurrence, and suggests the respective adaptation strategies. However, there is no one-size-fits-all adaptation strategy and different adaptation measures will be required for different crops and for distinct changes in temperature and precipitation. For this reason, insights to support adaptation include better knowledge about quantitative relationships between these critical weather inputs, their interaction, and their impacts on crop productivity per unit area (i.e., yield) at the farm level. Therefore, place-

based insights into weather-crop dynamics under climate change will help for a better spatial targeting of adaptation investments.

There is strong evidence of historical and recent climate change in Ukraine, particularly with respect to rising temperatures in winter (Morgounov et al. 2013). Moreover, precipitation seems to be decreasing in the southern Steppe zone of Ukraine during 1961-2009 (Morgounov et al. 2013). Climate change projections by the Intergovernmental Panel on Climate Change (IPCC) suggest that the temperature in the grain-producing areas of Ukraine will increase, with the greatest increase expected in winter months. Summer precipitation is likely to decline and winter precipitation expected to increase while droughts may become more likely and intensify (Lioubimtseva et al. 2013). However, to the best of our knowledge, the evidence of the historical and recent impacts of climate change on crop yields in Ukraine is scarce and we are not aware of any English-language publication that has assessed the effects of climate change on crop yields for all of Ukraine.

Ukrainian agriculture might experience positive outcomes from climate change in some regions because of increasing winter temperatures and winter precipitation, a longer frost-free season, and higher CO_2 concentration (Fischer et al. 2014, Lioubimtseva et al. 2013). Suitable croplands may expand in response to projected climate change, particularly in northern Ukraine, but the projections are subject to high uncertainty owing to unknown responses of agricultural land use with respect to the CO_2-fertilization effects on yields and unforeseeable adaptation developments (Osborne et al. 2013, Lioubimtseva et al. 2013). However, prolonged periods with summer temperatures far above the long-term mean may become the norm, particularly in the southern Steppe zone of Ukraine (Battisti and Naylor 2009), threatening crop production during a key period for crop development in this agriculturally most productive region with its widespread, fertile Chernozem soils (Lioubimtseva and Henebry 2012, Supit et al. 2012). Unfortunately, detailed assessments of how different scenarios of future climate change may affect wheat production in Ukraine are still missing.

Agriculture is a crucial sector for the Ukrainian economy and contributed on average 10 % to gross domestic product between 2005 and 2012 (World Bank 2016). Within agriculture, cereal production contributes about one third to total production value and is the most important land use in terms of area used. Overall, cereal production amounted to 42 million tons on average between 2005 and 2012 (World Bank 2016). Winter wheat is the dominant grain, occupying about 50% of all area cultivated with cereals (FAO 2016) and Ukraine was the 7th largest exporter of wheat in 2012 (FAO 2016). However, the high weather variability contributes to the high yield variability observed in Ukraine (Ray et al. 2015), and climate change will likely increase the production risk (Nikolayeva et al. 2012, Ministry of Environment and Natural Resources of Ukraine et al. 2013).

Predicting how climate change affects crop yields requires a model that captures the statistical association of the impact of weather inputs on crop output (Lobell and Burke 2010). There are two main types of models to forecast the effect of future weather conditions and agricultural management options on crop yields. First, process-based crop simulation models allow simulating site-specific growing conditions and measuring biomass and yields in an experimental model environment. Crop simulation models are also powerful in assessing the impact of various crop management options on yields, which is important with regard to the assessment of farmers adaptations options to climate change (Lobell et al. 2009, Asseng et al. 2013). However, the calibration of crop simulation models that emulate plant growth, and thus yields, necessitates a

number of subjective decisions to decide on several uncertain parameters as well as a wide range of input data, such as daily weather information, and experimental information (e.g., crop phenology) to specify key model parameters (Schierhorn et al. 2014, Lobell and Burke 2010). Unfortunately, data and information from such experiments are rare and not evenly distributed across space, and many regions completely lack experimental evidence that would allow generating the parameters necessary to capture hydrological and plant growth processes.

A second important approach to establish the relationship between crop yield and weather are statistical models that relate historical data of crop yields, temperature, and precipitation. Statistical models also indirectly capture the effect of other factors, which are not directly addressed, such as through the inclusion of observed yields that implicitly accounts for human and environmental adaptation to changing site conditions during the observation period because it incorporates the yield responses to input applications (Lobell and Burke 2010, Gornott and Wechsung 2016). For example, farmers tend to decrease fertilizer input when weather conditions become drier, water stress limits plant growth, or drought risk increases. Hence, the weather effects result in changes in crop management, which in turn impact on crop yield. In this report, we employ a statistical approach because of the lower demands for field data to calibrate and validate the models, a lower degree of subjectivity, and lower requirements to assess the uncertainty of estimates.

Our goals here were twofold: First, we aimed to establish the statistical relationships between observed wheat yields and weather input data for distinct environmental zones within Ukraine and for all of Ukraine. Using these relationships, our second aim was to predict the potential consequences of scenarios of future climate change from the IPCC for wheat yields. In doing so, we are able to approximate the impending yield effects of climate change in absence of adaption measures, such as plant breeding or land management. Such insights are important to highlight potential effects of climate change on crop production, reveal the uncertainty of crop yields in alternative climatic futures, and allow to anticipating the potential costs of inaction in terms of lost production as well as the benefits of adaptation.

The results suggest that it will be critical for Ukrainian agriculture to develop adequate adaptation measures in the southern steppe areas in order to address the effects of climate change on agricultural productivity. Our results further emphasize the importance of investing in breeding efforts to develop adaptive crop varieties that are tolerant to likely future climate conditions, such as heat stress and temperature-induced water stress.

2. MATERIAL AND METHODS

2.1. Climatic conditions and environmental zones

Ukraine has a continental climate with hot summers and cold winters. Rainfall is gradually decreasing and temperature increasing from north to south (Figure 1). About 48 % of the country is covered with highly fertile Chernozems (black soils), predominantly in the southern regions (FAO et al. 2009). Chernozems are very fertile because of high organic matter content and favorable structure of the upper soil horizon that provides deep water percolation (Driessen et al. 2000).
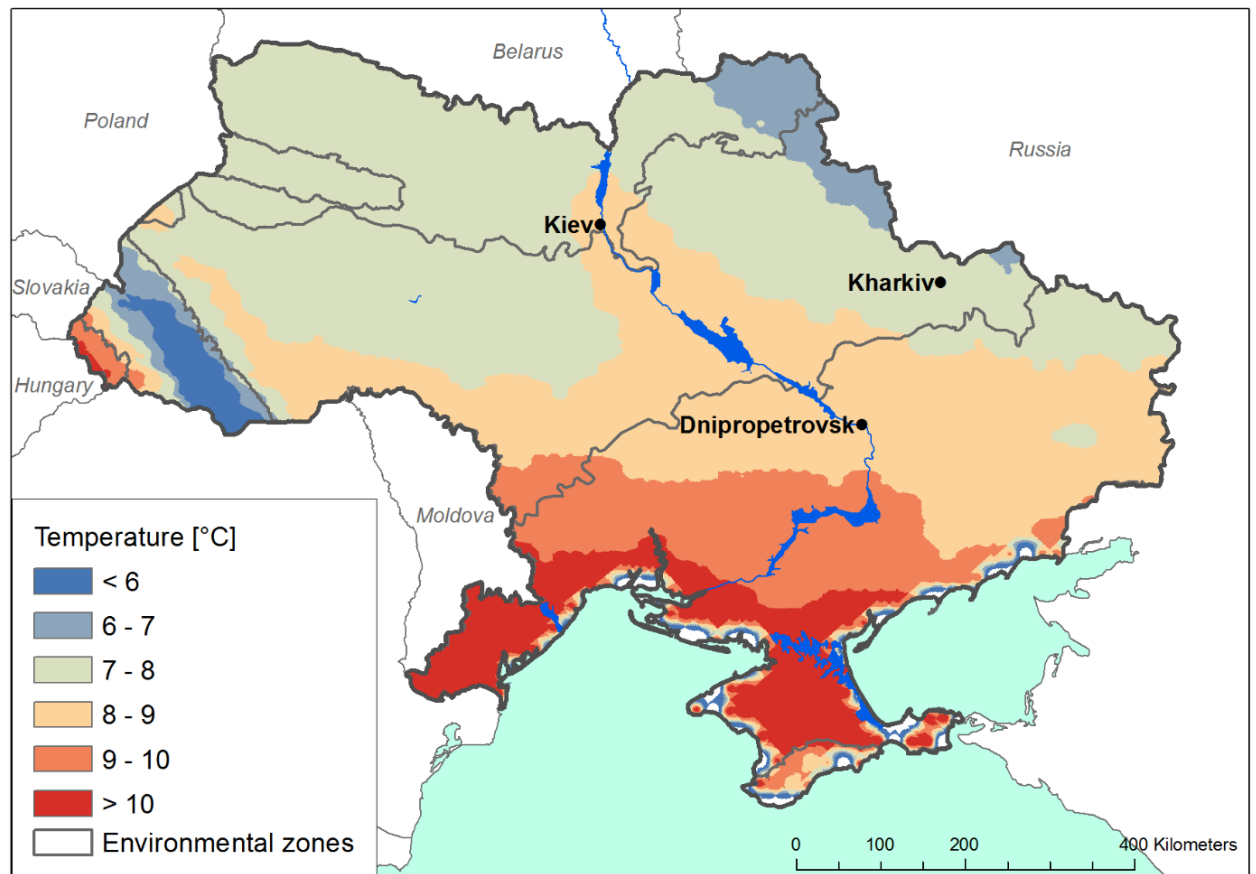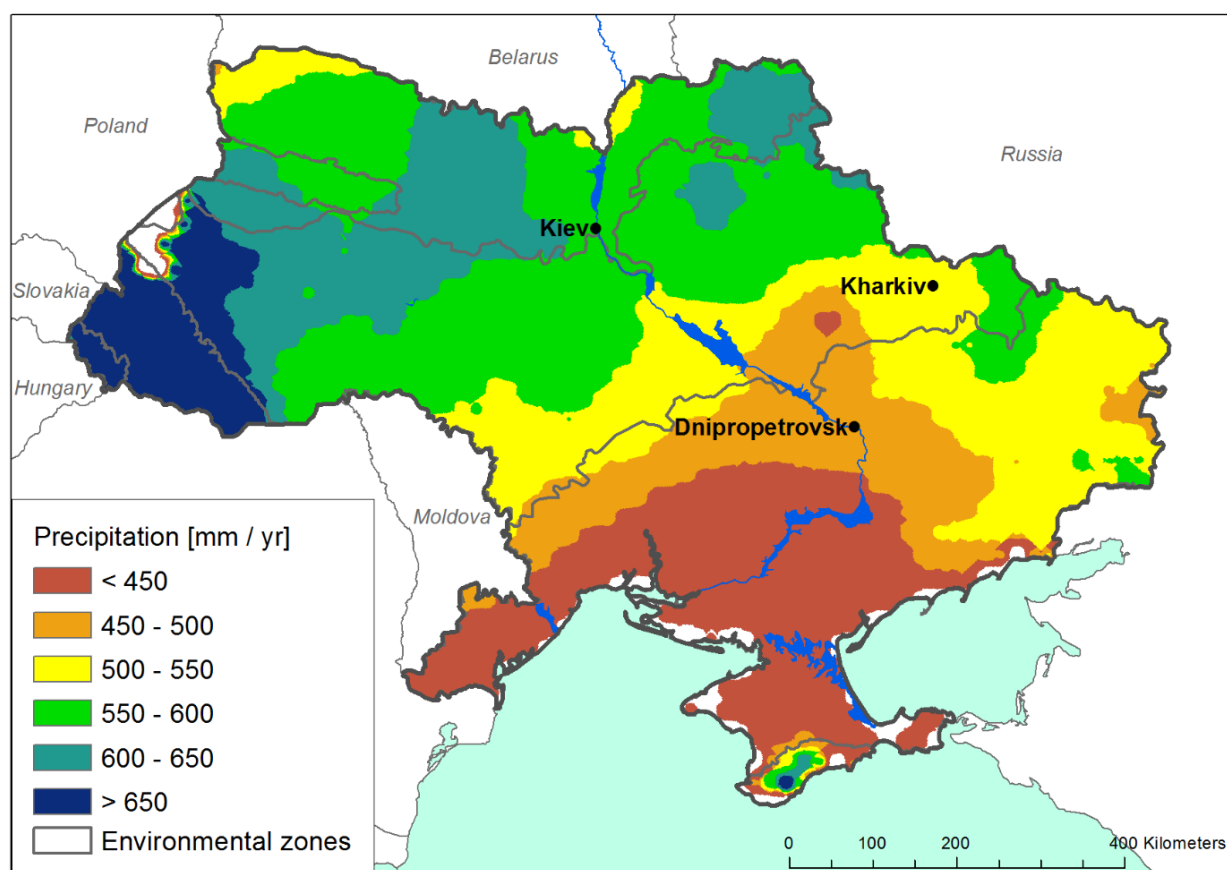
Figure 1: Average annual temperature (°C) and precipitation (mm) in Ukraine, 2005 to 2012

Note: White areas within Ukraine indicate missing data. The environmental zones are shown in Figure 2 below.

Climatic and soil conditions allow dividing Ukraine into three zones that are characterized by distinct environmental conditions, which are important for agricultural production (for more details on the characteristics of the zones, see Keyzer et al. 2012, Zastavniy 1994): The Mixed Forest, the Forest Steppe and the Steppe zone (*Figure 2*). Two other zones in Ukraine are the Carpathian Mountains in the West and the Crimean Mountains in the South, which we ignore in this report because of very little wheat production in these regions.

Figure 2: Environmental zones of Ukraine

The Mixed Forest zone accounts for 19% of the Ukrainian territory and is part of the Polesian lowlands. It is dominated by high groundwater tables, large swamp areas, and soils with low fertility and high acidity. The climatic conditions in the Mixed Forest zone are favorable for agriculture with sufficient precipitation and available solar energy. Mainly cereals, forage crops, potatoes, and flax grow well, as long as farmers provide sufficient amounts of fertilizer and lime. Besides agricultural land use, large areas in the Mixed Forest zone are occupied by grasslands and forests.

Further south begins the Forest Steppe zone that covers about one third of the country area and enjoys the highest crop yields in Ukraine. While naturally the vegetation in the Forest Steppe zone would be dominated by forests, most land is now used for agriculture. The combination of fertile Chernozem soils, sufficient supply and adequate temporal distribution of precipitation (500-600 mm per year), as well as favorable temperatures provide very suitable conditions for crop cultivation. Agriculture in the Forest Steppe is dominated by cash crop production, namely wheat, maize, barley, oil crops, sugar beet, and vegetables. The main risks for agriculture in the Forest Steppe zone are heat stress and frost stress for winter crops in the absence of protective snow cover due to the continental climate conditions with very cold winters.

The Steppe zone in Southern Ukraine provides excellent natural conditions for agriculture, with more than 80 % of the Steppe zone covered by fertile Chernozem soils (FAO et al. 2009). However, low precipitation rates and frequent extreme summer temperatures cause water and heat stress, respectively, and thus limit crop yields. The high climate and yield variation in the

Steppe zone may reduce investments of farmers into intermediate inputs, such as fertilizer and pesticides, because these inputs may be lost in the case of crop shortfall. The most important cultivars in the Steppe zone are winter wheat, sunflower, maize, and barley, which are typically grown on large fields and at low intensity levels, with low average yields.

2.2. Data sources

2.2.1. Farm-level data

We used the statistical database of the Ukrainian Agribusiness Club (hereafter, UCAB database). The data cover more than 15,000 farms that reported farm-level data on agricultural production, sales, and input use between 2005 and 2012. All agricultural enterprises in Ukraine are included in the database as well as a substantial share of the family farms. The large number of households who are active in agriculture are not included in the database. The UCAB database therefore excludes smallholders but includes most commercially oriented and larger farms and covers the majority of cultivated land in Ukraine.

The data include, inter alia, also the address of each farm, which we used to derive the geographic coordinates of the farms. We then intersected the farm coordinate with a 250m resolution global land-cover map (the Finer Resolution Observation and Monitoring, Global Land Cover (FROM-GLC), Yu et al. 2013) to approximate the spatial extent of the cropland of each farm. To do so, we assigned the area of cultivated cropland reported in the farm survey to the land-cover map, assuming that 1) farms have their cropland in the vicinity of the reported farm address and 2) areas that are designated as cropland in the land-cover map are preferred to areas that have a mix of cropland and other uses reported from the satellite-derived maps (e.g., cropland-forest mosaics). This spatial allocation approach resulted in a high-resolution cropland map that was used to assign weather and climate data to the farms and to visualize the spatial distribution of reported and projected wheat yields.

For our analysis, we selected the 12,993 farms from the UCAB database data that reported winter wheat production in at least one out of the eight years included in the data. The selected farms account for more than 60% of the national production of winter wheat between 2005 and 2012. We excluded 67 large agro-holdings, each with an area of over 400 km^2 (40,000 ha), from the allocation procedure because these typically operate on multiple, spatially disconnected sites of production but are registered with a single address only. As a result, the assignment of the farm address with the location of cropland for these farms was impossible.

2.2.2. Historic climate data

The European Climate Assessment & Dataset (ECA&D) provides the ENSEMBLES Observations gridded dataset (E-OBS) with daily meteorological observations throughout Europe with a spatial resolution of 25 km (Haylock et al. 2008). We obtained the E-OBS dataset from the data providers of the ECA&D project (www.ecad.eu). The data are based on daily observations from European climate stations. We downloaded the E-OBS dataset version 11.0 on August 2nd, 2015 for the period from Jan 1st, 1950, to Dec 31st, 2014.

We used precipitation, temperature, and evapotranspiration as weather inputs. Temperature and precipitation determine plant growth by driving water balance and energy availability while evapotranspiration captures the loss of water during the growing season. We used daily values of the E-OBS weather data from 2005 to 2012 to calculate average temperature and the sum of

precipitation and evapotranspiration over each growing period of winter wheat (see section 2.2.4 and Table 1 below). Daily values for evapotranspiration were calculated from the extraterrestrial radiation and the minimum, maximum, and mean temperature using Hargreaves equation that allows to estimate reference evapotranspiration (Allen et al. 1998).

We calculated the centroid of the cropland area of each farm (see section 2.2.1) and transferred the weather data and the climate change projections of this centroid to the farm data. The data for temperature, precipitation, and evapotranspiration were used to create raster data at a spatial resolution of 1 km² using inverse distance weighted (IDW) interpolation. The raster layers were then extracted for the approximated area of each farm (section 2.2.1).

2.2.3. Trajectories of future climate change

Moss et al. (2010) introduced four Representative Concentration Pathways (RCP) that replaced the previously used climate change scenarios in the Fifth Assessment Report of the IPCC (Collins et al. 2013). The four RCP represent different trajectories of greenhouse gas concentrations in 2100 relative to the pre-industrialization level in 1850. The names of the RCP signal the amount of radiative forcing, expressed in Watts per square meter (W/m²). For example, RCP 2.6 represents an increase in energy intake of 2.6 W/m² in 2100 relative to the levels in 1850. Other commonly used RCP trajectories indicate an increase of 4.5, 6.0, and 8.5 W/m². The RCP trajectories serve to parameterize global circulation models with the corresponding greenhouse gas concentrations in order to approximate their effect on the global climate system. Corresponding scenarios about socioeconomic developments, such as population density, land use, and energy usage, can then be assigned to the respective RCP.

The most optimistic future trajectory, RCP 2.6, may keep the global average temperature increase below 2°C until 2100, but only if the global community can rapidly and substantially reduce emissions (IPCC 2014). The other trajectories imply a global average temperature increase of 2.6°C (RCP 4.5) and 4.8°C (RCP 8.5) relative to pre-industrialization levels. Here, we used RCP 4.5 and RCP 8.5 because these two trajectories seem most realistic at the time of writing while still spanning a large range of future greenhouse gas concentrations.

The IPCC also summarized future climate predictions using a multi-model comparison with the uncertainty range of projections provided by the different model outcomes (IPCC 2013). We use projections of future climate change from data created by the Coordinated Regional Climate Downscaling Experiment (CORDEX, see Jacob et al. 2013). The data for the European CORDEX area are available in daily temporal resolution and with a 0.11° spatial resolution (approximately 12 km) at climate4impact.eu (download on February 18th, 2015). These data were produced by downscaling the global data with the Rossby Centre regional atmospheric model (RCA4, see Strandberg et al. 2014), which in turn is based on results from the five global circulation models (the CNRM-CM5 (Centre National de Recherches Métérologiques, France, and Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France), EC-EARTH (Irish Centre for High-End Computing, Ireland), IPSL-CM5A-MR (Institut Pierre Simon Laplace, France), HadGEM2-ES (Met Office Hadley Centre ESM, GB), and MPI-M-ESM-LR (Max-Planck-Institut für Meteorologie, Germany)).

To compare the historic with the predicted data, we had to combine the measured and interpolated EOB-S data from ECA&D with the modeled CORDEX data for future climate change. To do so, we normalized both the EOB-S and CORDEX data for the period 1976 to 2005 to one (i.e., we set the country-wide mean from 1976-2005 = 1). The normalization procedure corrects for

systematic biases between the observed and modelled data sources. We used the modeled RCP 4.5 and RCP 8.5 data from 2010 to 2070 to assess the impact of future climate conditions on wheat yields using the statistical relationships for historic weather-yield associations that were calculated using the methods explained in section 2.3.

2.2.4. Aggregation of climate data for growing periods of winter wheat

Because the wheat plants have specific demands in terms of weather inputs during each growing period, we aggregated the weather input data and climate change scenarios for each of the growing periods of winter wheat. The FAO defines the following growing periods for winter wheat (www.fao.org/nr/water/cropinfo_wheat.html):

- Establishment (10-15 days),
- Vegetative (15-25 days in autumn, winter dormancy, and 40-50 days in spring),
- Flowering (15-20 days),
- Yield Formation (30-35 days), and
- Ripening (10-15 days).

Naturally, these definitions for growing periods are a generalization because plant growth depends on weather conditions and crop management.

Although plant development can be subsumed in one vegetative period spanning from autumn to spring with a dormancy of around 100 to 120 days in winter, the plant requirements differ between the seasons. Therefore, we considered the second part of the vegetative phase separately (i.e., after the winter dormancy) because we wanted to explicitly analyze the climate at the periods when the plants were not dormant. We therefore merged the time before the winter dormancy into a first vegetative period under the assumption that the seedlings have similar requirements during the establishment and early vegetative phase in autumn and because both periods are very short. The FAO defines planting dates for winter wheat in different climate conditions at www.fao.org/docrep/x0490e/x0490e0b.htm. The climate conditions and planting dates of Idaho, USA, are closest to the conditions in much of Ukraine. We therefore selected October 1st (the planting date in Idaho) as the start of the first vegetative period that lasts for 46 days (Table 1). After the winter dormancy with the frost that enables vernalization, the plants start actively growing during the second vegetative period at the beginning of May; accordingly, we defined the second vegetative period from May 1st until June 15. The 15 days of the flowering period until end of June are followed by one month for yield formation, and, starting on August 1st, by 15 days for ripening (Table 1). After mid-August, the harvest time for winter wheat commences in Ukraine. These insights are, of course, generalizations but synthesize well the available literature and the various personal communications that we had with farmers and agricultural exports in Ukraine.

Table 1: Growing periods of winter wheat

Name	Length (days)	Duration
1st vegetative period	46	October 1st to November 15th (previous year)
2nd vegetative period	46	May 1st to June 15th
Flowering period	15	June 16th to June 30th
Yield formation	31	July 1st to July 31st

Name	Length (days)	Duration
Ripening period	15	August 1st to August 15th

Source: FAO Water Development and Management Unit (www.fao.org/nr/water/cropinfo_wheat.html)

Unfortunately, no information was available for specific growing periods within the environmental zones of Ukraine. We therefore proceeded with using the approximated growing periods in Table 1 for the three environmental distinct zones as well as for all of Ukraine.

2.3. Statistical model

To determine the statistical relations between weather data and wheat yields, we use random forests (Cutler et al. 2007, Breiman 2001) with the package "randomForest" (Liaw and Wiener 2002) in statistical software R (R Development Core Team 2012). Random forests are based on decision trees, which are statistical algorithms that segment the data into homogenous subgroups. Random forests use a large number of decision trees (hence, a "forest"). The predictive capacity of random forests are improved by randomly choosing a different set of input variables (hence, "random" forests). In random forests, a decision tree will be fitted to each sample and at each node of the tree on a different subset of the randomly selected input variables in order to find the best binary split. In sum, random forests generate accurate predictions while not overfitting the data, which results in the great ability of random forests for generalization (Breiman 2001). Random forests are particularly apt for the analysis of large datasets and for detecting non-linear relationships (Prasad et al. 2006, Estel et al. 2015).

We calculated separate random forest models for the three environmental zones (Mixed Forest, Forest Steppe, and Steppe) to account for the regional heterogeneity and a fourth model for the entire country. The unit of analysis was the farm area to which the climate data have been assigned. We estimated the mean effects for all years covered in the UCAB database (2005-2012). To account for the temporal variation, we pooled the data, so that we obtain one data row per farm in each year when winter wheat was planted and then we associated the climate data of the respective year with the yield data. If a farm planted winter wheat in all eight years, then this farm would receive eight data values. The statistical relationships based on the historic data of weather and wheat yields were then used to predict wheat yields until 2070 using the data of the two scenarios of climate change.

3. RESULTS

3.1. Wheat yields

The spatial allocation of farmland allows to map reported and projected wheat yields at high spatial resolution. Figure 3 visualizes the spatial distribution of average winter wheat yields between 2005 and 2012. The highest yields are observed in the Forest Steppe zone, which provide the best natural conditions. The wheat yields are substantially lower in the Mixed Forest zone due to lower soil fertility. In the Steppe zone, the limited water availability in combination with high summer temperatures reduce yields, particularly towards the southern part of the Steppe zone. The map also demonstrates the lower share of cropland in the Mixed Forest zone, reflecting the large wetland areas as well as the harsh winter conditions with regular frost damage that inhibit crop production. Moreover, some of this area is still contaminated from the nuclear meltdown in Chernobyl in 1986 and thus remains abandoned (Hostert et al. 2011).
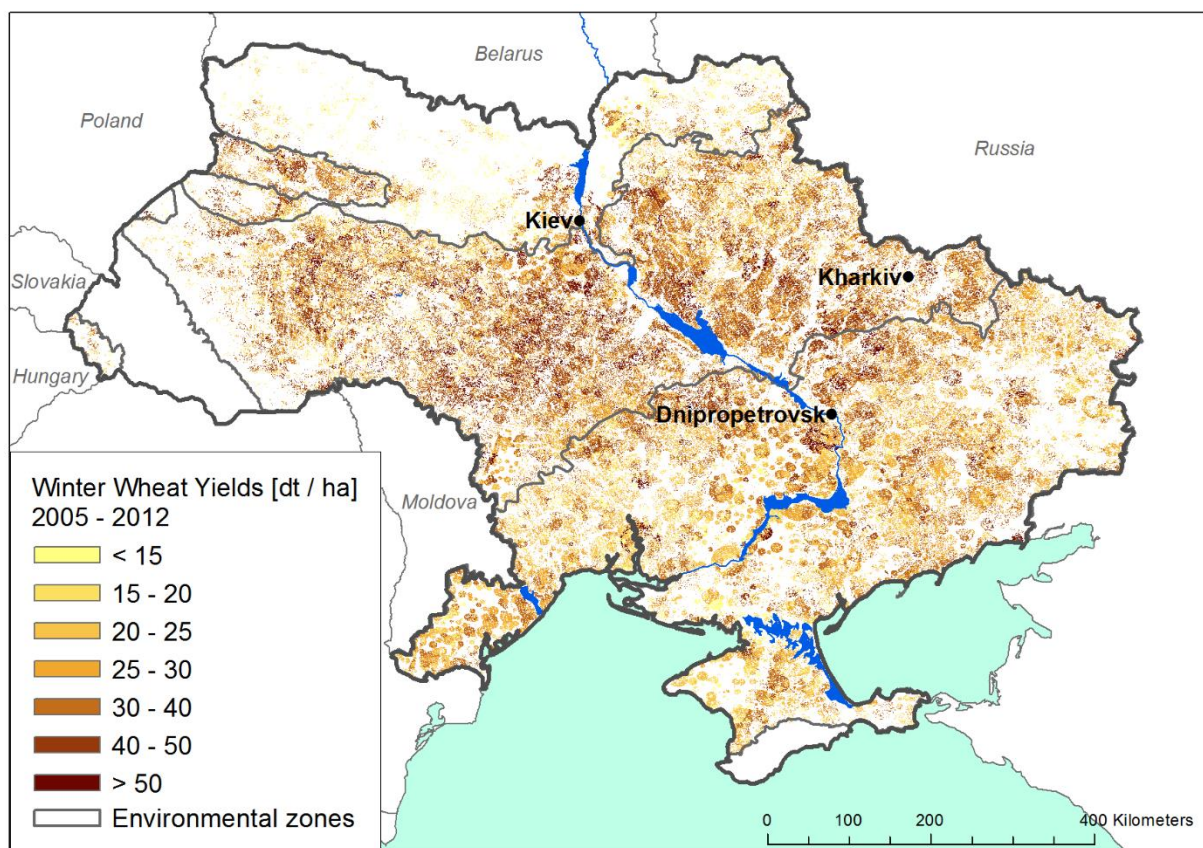

Figure 3: Distribution of average yields of winter wheat between 2005 and 2012

The average sown area of winter wheat per farm in the UCAB database was 521 ha. Between 2005 and 2012, the UCAB database covers an average of 2.95 Million hectares (Mha) of harvested area of winter wheat in total, ranging from 3.0 Mha in 2006 to 4.2 Mha in 2008. Almost 95 % of this area is located in the Forest Steppe and Steppe zones (Table 2).

Table 2: Key indicators from the farm data used in this report

Zone	Farms (Number)	Farm area (Mha)	Harvested area of winter wheat		Production of winter wheat	
			(Mha)	(%)	(Mt)	(%)
Mixed Forest	1,397	1.47	0.16	4.3%	0.43	3.8%
Forest Steppe	6,618	10.46	1.57	43.3%	5.41	47.7%
Steppe	4,976	9.62	1.90	52.4%	5.50	48.5%
Ukraine	*12,991*	*21.56*	*3.63*	*100%*	*11.34*	*100%*

Source: Own calculations based on UCAB database; MT = million tons; Mha = million ha.

Mixed Forest zone

Total cropland area in the Mixed Forest zone is 2.77 Mha, which is equivalent to 8.4 % of all cropland in Ukraine (Figure 3). 1.47 Mha or 6.8 % of the total arable land reported in the UCAB database are located in the Mixed Forest (Table 2). Winter wheat occupies only 0.12 Mha (10.6 %) of the reported cropland because of frequent frost damage and poor soil quality. Wheat yields of farms in the UCAB database are lowest in the Mixed Forest zone with 18.6 dt/ha on average, ranging from an average of 13.2 dt/ha in 2006 to 27.1 dt/ha in 2012 (Figure **4**), and resulting in an average production of 0.31 Mt between 2005 and 2012 (3.8 % of total production of winter wheat in the UCAB database). The UCAB data contains 1,397 farms in this zone (Table 2).
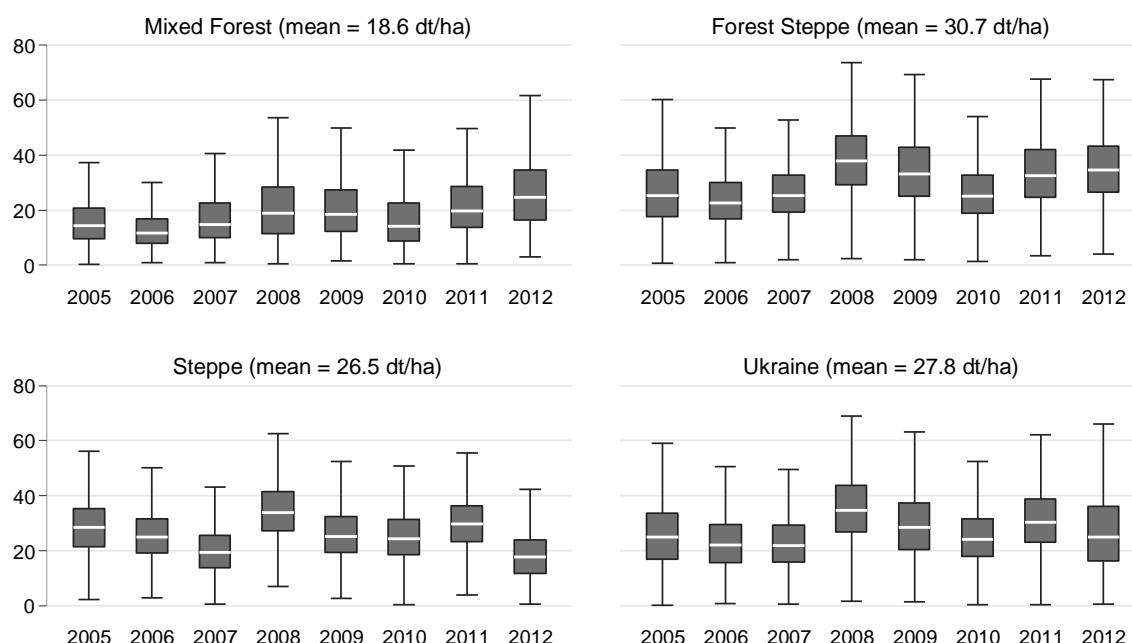
Figure 4: Yields of winter wheat between 2005 and 2012

Note: Box plots exclude outside values that are smaller than the lower (upper) quartile minus (plus) 1.5 times the interquartile range of the values. All wheat yields were area-corrected and capture yields per hectare (as compared to the average yields per farm that were reported in the UCAB database).

Forest Steppe zone

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The Forest Steppe zone harbors more than 12.58 Mha of cropland and is the most important crop producing zone in Ukraine. Winter wheat accounts for 15% or 1.57 Mha of the 10.46 Mha that are reported in the data for this zone. The Forest Steppe zone enjoys the highest yields of winter wheat with an average of 30.7 dt/ha between 2005 and 2012, ranging from 23.9 dt/ha in 2006 to 38.5 dt/ha in 2008. The yield variations across years mainly reflect the volatile weather conditions. The UCAB data contains 6,618 farms in this zone, which together produce on average 5.41 Mt of winter wheat per year.

Steppe zone

Agriculture in the Steppe zone is dominated by low crop yields because high summer temperatures, low precipitation, and low applications of intermediate inputs limit crop growth. Evapotranspiration are high and severe droughts occur regularly. Total cropland area amount to 17.44 Mha in the Steppe zone. The 4,976 reported farms in the UCAB database from the Steppe zone reported on average 9.62 Mha of cultivated area between 2005 and 2012. Winter wheat production that occupies 1.9 Mha or 20 % of the croplands in this zone, with an average production of 5.5 Mt per year between 2005 and 2012, equivalent to 52.4 % of all winter wheat production in the UCAB database. Average winter wheat yields for that period were 26.5 dt/ha, ranging from 18.7 dt/ha in 2012 to 35.0 dt/ha in 2008. The Steppe zone thus exhibits the highest volatility in wheat yields.
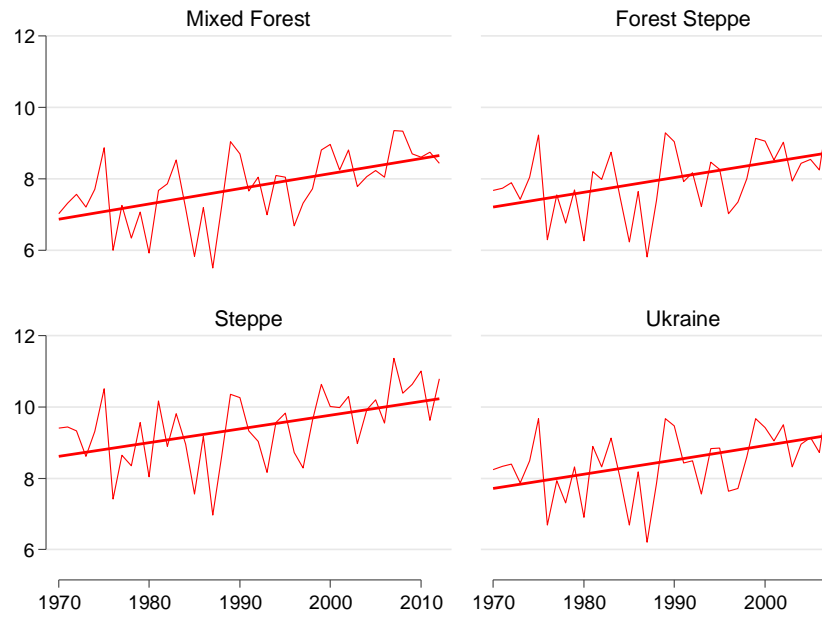
Ukraine

In total, we considered 12,991 farms in the analysis with an average area-corrected yield of winter wheat of 27.8 dt/ha, varying between a low of 23 dt/ha in 2006 to 35.6 dt/ha in 2008 (Figure **4**). Total harvested area in the UCAB database that we considered was 21.56 Mha and 11.34 Mt of winter wheat were harvested on 3.63 Mha (17 %) of the farmland (Table 2).

3.2. **Historic weather patterns**

Since 1970, Ukraine experienced increasing temperatures and evapotranspiration (all trends for temperature and evapotranspiration in Figure 5 are positive and statistically significant at the 1%-level), while none of the precipitation time series in Figure 5 are statistically significant. The high fluctuations from year to year are indicative of the highly variable weather conditions, which arguably reduce farmers' decisions on investment into crop production and thus negatively affect agricultural production.

Temperature (°C)
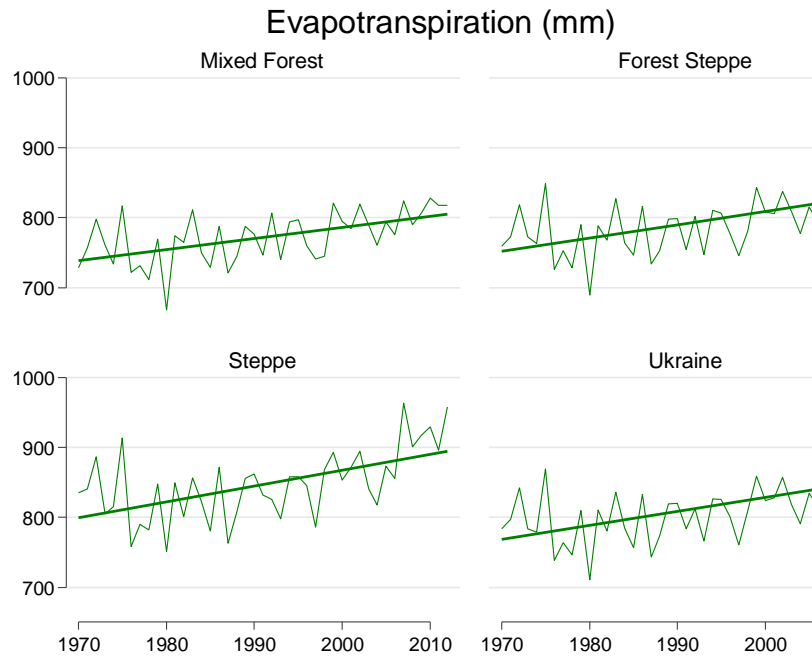

Precipitation (mm)
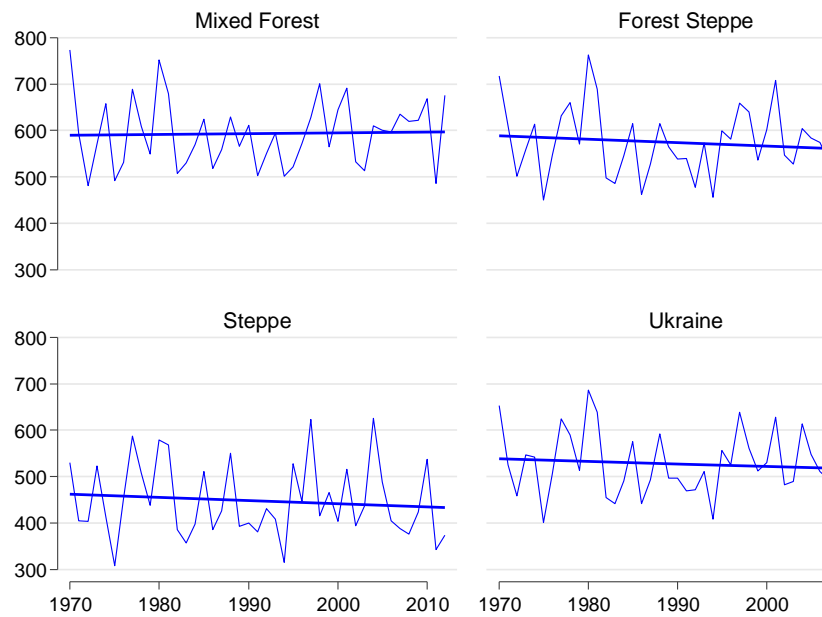
Figure 5: Climate variations in Ukraine, 1970 to 2012

Source: Own calculations based on EOB-S data that were disaggregated to the farm level and then averaged for the environmental zones; thick lines indicate linear fit.

The statistically significant trends in Figure 5 suggest temperature increases between 1.61 °C in the Steppe up to 1.80 °C in the Mixed Forest between 1970 and 2012, amounting to an average increase of about 0.04 °C per year. Evapotranspiration was increasing from between 67 mm in the Mixed Forest up to 95 mm in the Steppe.

3.3. Relationships between weather input and wheat yield

The predictive power of the models was good, particularly considering that we only used weather inputs in the analysis (Table A 1). The scatter plots that compare observed crop yield with predicted crop yields (Figure A 6) show that the random forest model seems to systematically underestimate wheat yields for high yield values while it slightly overestimate yields at low yield levels. Most likely this is because we have not included variables that capture effects of agronomic management, such as fertilizer applications or irrigation. Yet, overall, the results substantiate the important role of weather inputs for yields and therefore justifies our methodological approach.

The random forest models allow calculating the importance of each variable for the model fit (shown in Figure 6) and the partial dependence plots (PDP) that depict the direction of influence of each variable on the outcome variable wheat yield (see Figure A 2 to Figure A 5).

At the level of the environmental zones, the results suggest that temperature and evapotranspiration during the second vegetative periods as well as temperature during the period of yield formation were the most important variables in the Mixed Forest (Figure 6). Conversely, precipitation was a key determinant for wheat yields in the Forest Steppe with the largest influence in the second vegetative period and ripening period, while temperature was important in the sec-

ond vegetative period. In the Steppe zone, temperature was crucial for wheat yields mainly during the second vegetative period and, to a lesser extent, in subsequent periods. Subsequently, we concentrate the interpretation of the results on the three to four variables per zone that have the highest influence on the outcome.
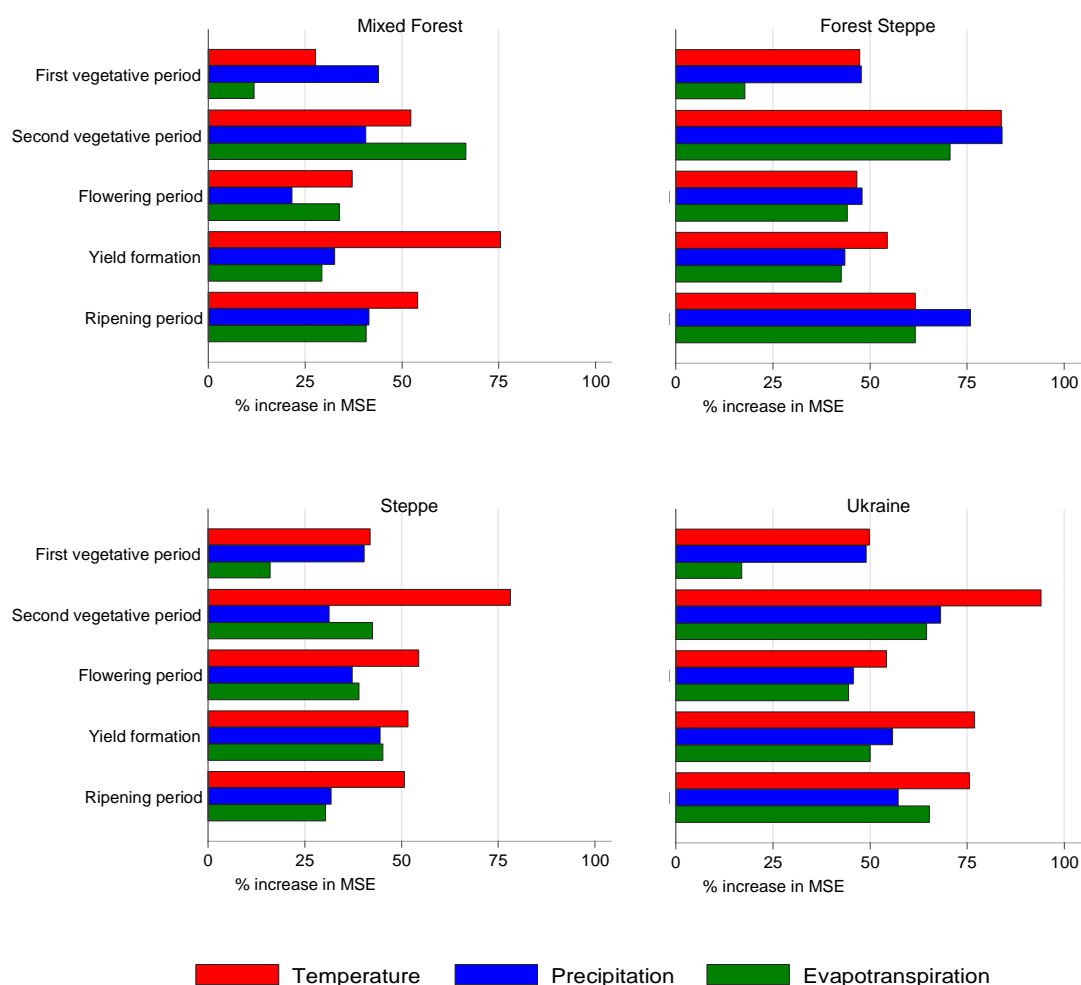

Figure 6: Variable importance for each growing period

Note: The graph captures the importance of each variable in each growing period by measuring the increase in model error (measured as the mean squared error, MSE) that results from removing the particular variable from the model. In other words, variables that are important in determining yields of winter wheat have high values in the Figure 6. However, the direction of the variable influence cannot be discerned from this figure.

In the Mixed Forest zone, the results show that increasing temperatures, compared to the baseline climate of 1976 to 2005, during yield formation may substantially increase future wheat yields (Figure A 2). To a lesser extent, higher temperature and evapotranspiration during the second vegetative period and higher temperature during ripening may also stimulate future wheat yields in the Mixed Forest zone.

The most important weather conditions for wheat yields in the Forest Steppe zone occur during the second vegetative period and the ripening period (Figure 6). In the second vegetative and the ripening period, lower precipitation and lower evapotranspiration but similar temperature

compared to the baseline climate conditions between 1976 and 2005 will facilitate higher yields at (Figure A 3).

In the Steppe zone, the variables with the highest importance are associated to the temperature conditions. Two distinct trends in the marginal effect of temperature on yields can be identified (see Figure A 4): In all growth phases, except during yield formation, lower temperatures were associated with higher crop yields. The temperature optimum is likely to occur at temperatures comparable to the climate conditions in the 1976 to 2005 period (note that we normalized the temperatures to one) or slightly below. Higher temperatures in the yield formation phase, in contrast, correlate with higher yield in winter wheat. These results indicate that the increase in temperature that are projected for the Steppe zone during each of the growth periods (see Figure 7 and Figure 9) will likely lead to a decrease in winter wheat yields in the absence of countervailing adaptation measures. No clear conclusions can be drawn for both precipitation and evapotranspiration in the steppe zone.

For all of Ukraine, higher temperatures particularly during the second vegetative period in late spring and the ripening period will compromise wheat yields (Figure A 5) while higher temperatures may have a slightly positive effect during the yield formation phase.

3.4. Future climate change

Between 2010 and 2070, the CORDEX data suggest increasing temperatures throughout Ukraine, with an expected temperature increase between 1.65 °C (Steppe) and 1.74 °C (Forest Steppe) in RCP 4.5 and between 2.68 °C (Mixed Forest) and 2.98 °C (Steppe) in RCP 8.5 (Figure 7).
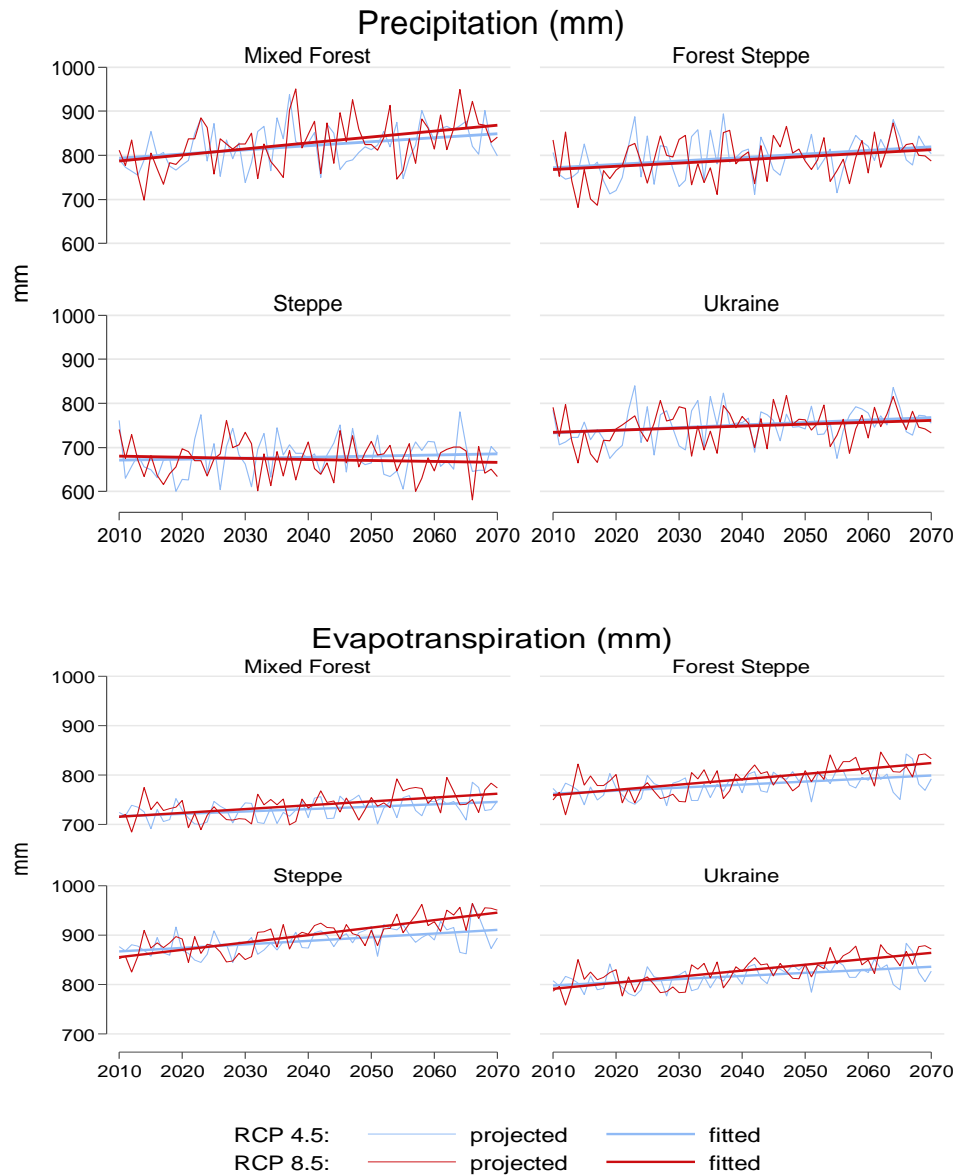

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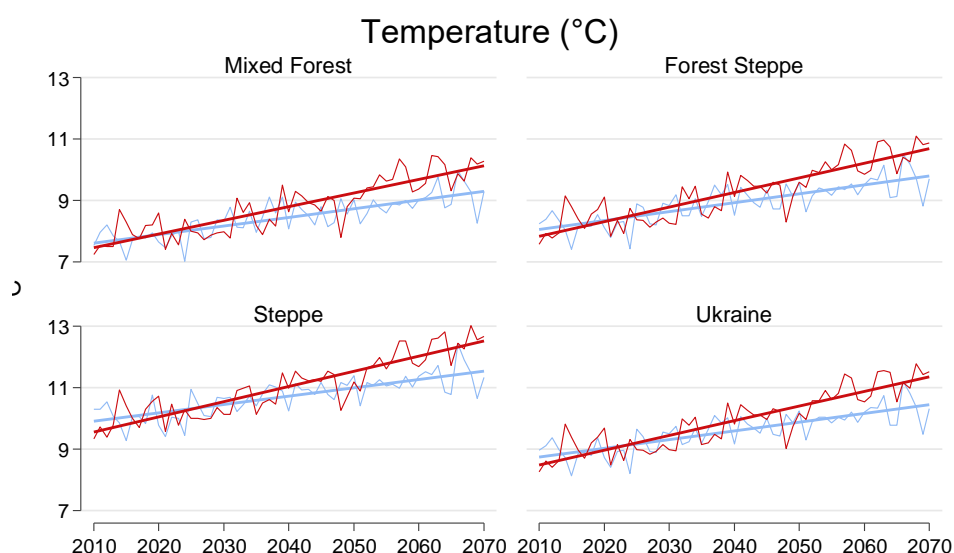
Figure 7: Projected climate change from 2010 to 2070 in RCP 4.5 and RCP 8.5

Source: Own calculations based on data from CORDEX; thick lines indicate linear fit.

According to the projections, average precipitation will likely be relatively less affected by climatic changes. In RCP 4.5, the increase in precipitation ranges from 13 mm in the Steppe zone to 55 mm in the Mixed Forest zone. Stronger changes are expected in RCP 8.5 with an increase above 80 mm in the Mixed Forest and a decrease of around 13 mm in the Steppe zone.

Evapotranspiration is most likely to increase in the future, mainly driven by higher temperatures. In RCP 4.5, evapotranspiration may increase by about 38 mm on average in RCP 4.5, while in RCP 8.5 the average increase in predicted evapotranspiration amounts to 72 mm. In both future trajectories, average increase in evapotranspiration is highest in the Steppe zone (Figure 7).

Figure 8 visualizes the spatial distribution of the expected changes in temperature and precipitation using the example of RCP 8.5 (we omit the maps for RCP 4.5 for the sake of brevity but they are available from the authors upon request). The maps in Figure 8 show the highest tem-

perature increase in central and eastern Ukraine, particularly in the steppe regions along the border with Russia. Precipitation is like to increase in most areas, except the southernmost fringes at the Black Sea. The highest increases of precipitation tend to occur in northern Ukraine, and particularly for the Mixed Forest zone, especially in the Carpathian mountain ranges. While the changes in precipitation are largely not statistically significant, there is evidence that it may show a downward trend in the Steppe region (see also Figure 7).
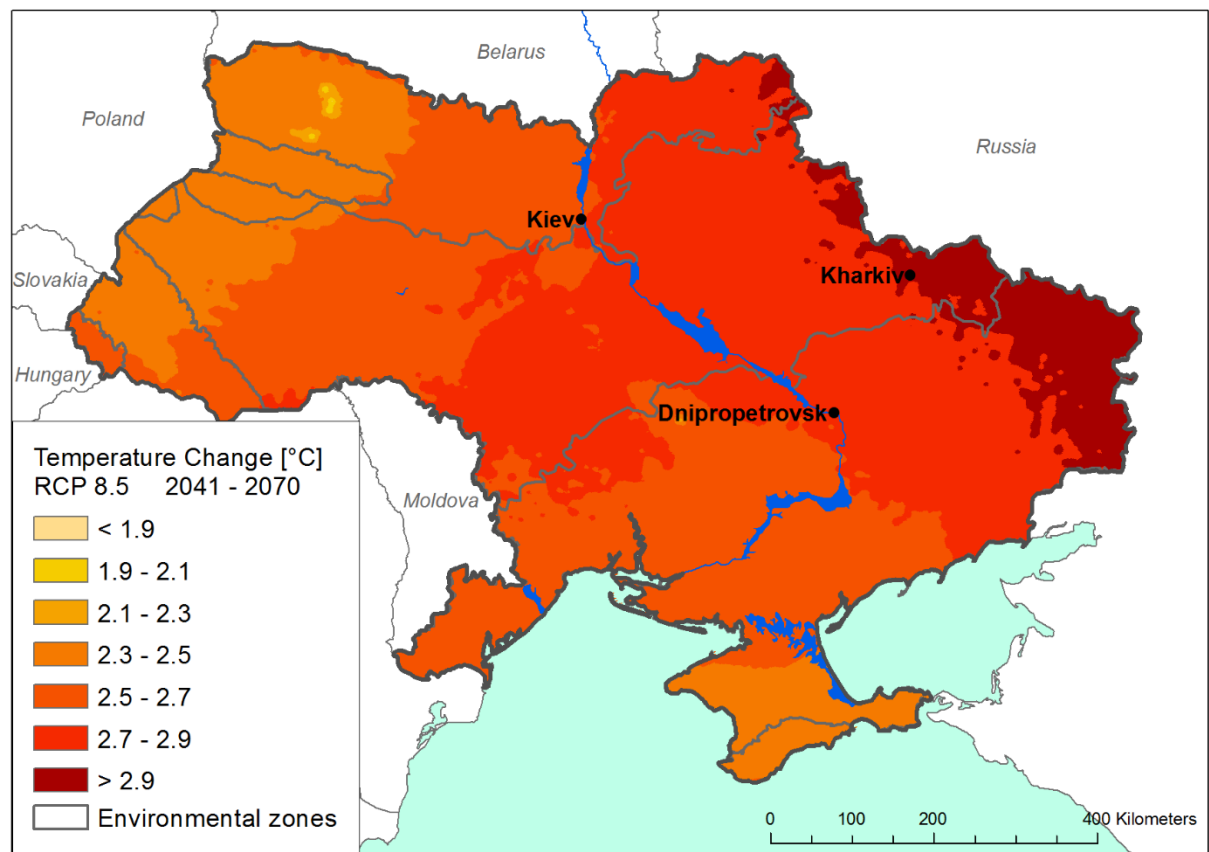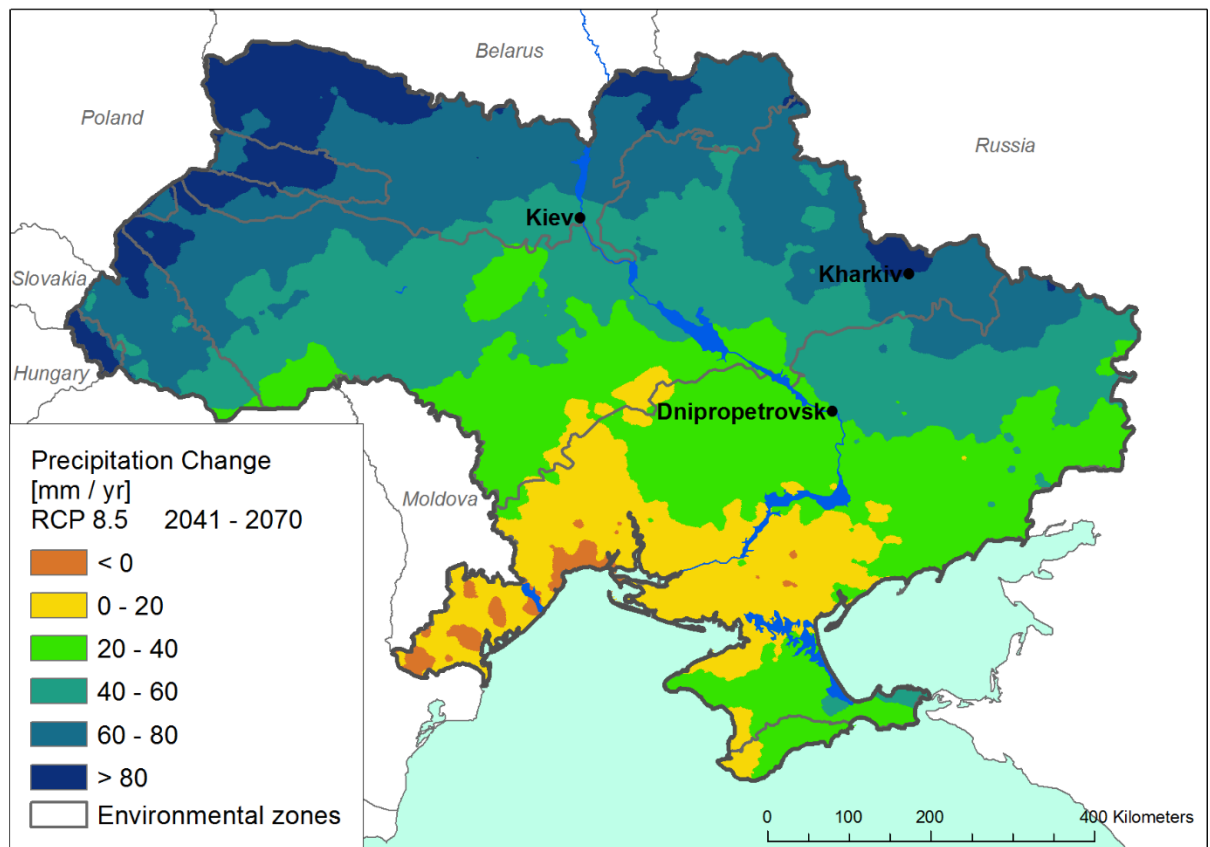
Figure 8: Average change of temperature and precipitation between 2040 and 2070 compared to 1976 and 2005 in RCP 8.5

Changes in weather conditions impact the growth of wheat plants differently in different growing periods. We have aggregated temperature, precipitation, and evapotranspiration for each of the five growing periods of winter wheat, all the environmental zones and for the two future emissions trajectories (Figure A 1). For example, Figure 9 shows the disaggregation of simulated future changes in temperature and precipitation in RCP 8.5 for the Steppe zone, which exhibits particularly strong and significant increases in temperature in all growing periods. The evidence for precipitation is again inconclusive, with only one statistically significant trend, which is the decrease of precipitation by about 10 mm in the flowering period. Temperature may increase by up to 4 °C in the flowering and yield formation periods, hence resulting in higher evapotranspiration (evapotranspiration is not shown in Figure 9 and Figure A 1, for the sake of brevity).
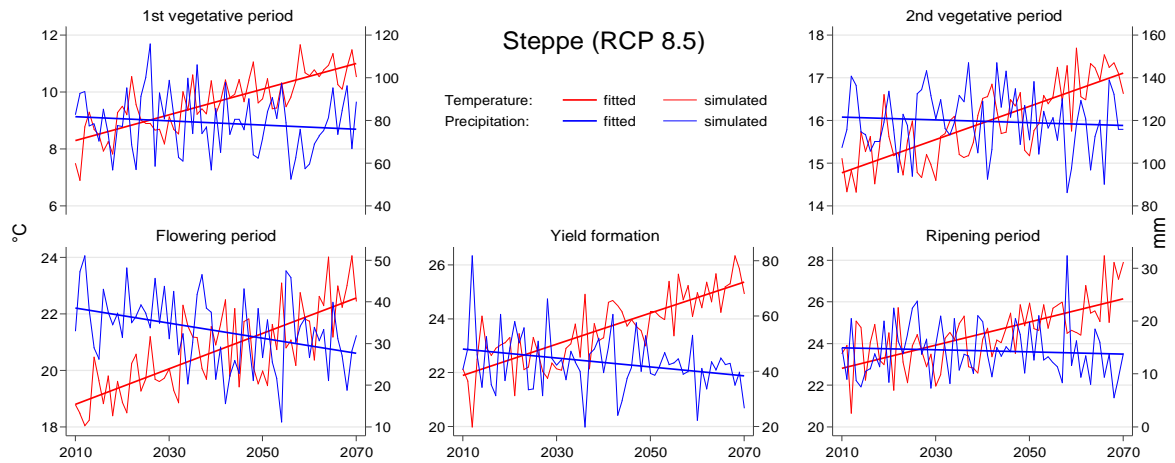
24

Figure 9: Changes in temperature and precipitation in the Steppe zone in RCP 8.5

3.5. Projections of yields and production of winter wheat under climate change

We used the calibrated random forest models and the CORDEX climate-projections to predict future wheat yields (Figure 10). The projected climate changes in both the RCP 4.5 and RCP 8.5 tend to increase wheat yields in the Mixed Forest zone. Most importantly, the model suggests decreasing wheat yields in the agriculturally important Steppe zone. The effects in the Forest Steppe will likely remain minor, arguably because the increasing temperatures will be compensated by increasing precipitation (Figure 7). Interestingly, average forecasted wheat yields in the national model will not change substantially compared to contemporary yields. We can also observe from Figure 10 that the variation of projected wheat yields is substantially lower for the model for all of Ukraine compared to the models for the environmental zones. We postulate that the lower variation is because regional specificities level out in the national model, which speaks in favor of our regionally disaggregated approach.

There are also clear differences between the two scenarios: In a world with a radiative forcing that is 4.5 W/m² higher compared to pre-industrial levels, the effects on yields of winter wheat will remain lower in all regions, with smaller increases in the Mixed Forest and smaller decreases in the Steppe zone. With 8.5 W/m², the expected yield increase will become much more substantial in the Mixed Forest zone and the expected yield decrease will be large in the Steppe zone.
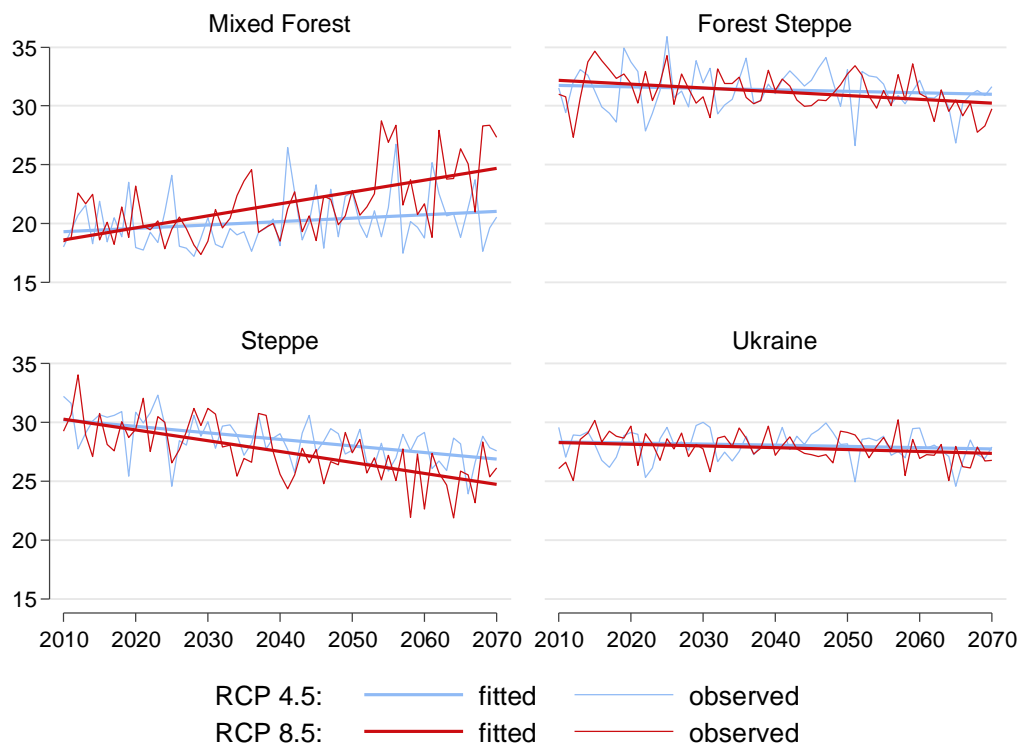
Figure 10: Projected changes of yields of winter wheat until 2070 in RCP 4.5 and RCP 8.5

We used the projected yields to approximate the effects of climate change on wheat production, using the average cultivated area between 2005 and 2012 as reference. Figure 11 shows that particularly the steppe region may suffer from substantial reduction in output by 2070, with 0.48 Mt less in RCP 4.5 (a reduction of 11%) and 0.81 Mt less in RCP 8.5 (-18%). In the Forest Steppe, wheat output will reduce much less by 0.1 Mt (-2.2%) in RCP 4.5 and 0.26 Mt (-6%) in RCP 8.5 while the Mixed Forest zone will see higher output, albeit at low levels because of the low acreage dedicated to wheat production and the lower yields. Overall, wheat production across all of Ukraine may decrease by 0.72 Mt in RCP 4.5 (- 6.5 %) and by 1.26 Mt (- 11.4 %) in RCP 8.5.
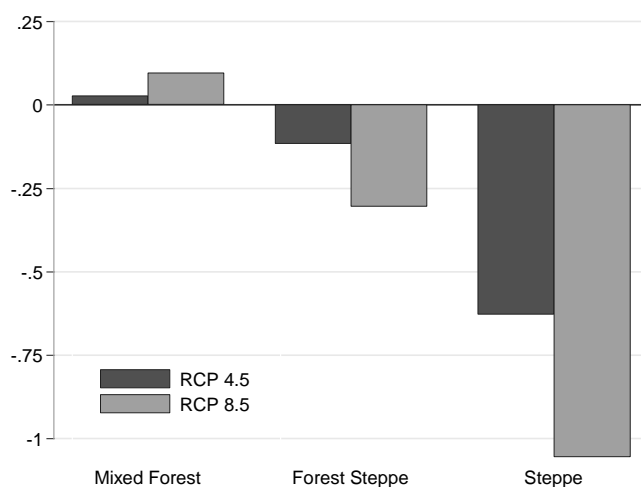

Figure 11: Change in winter wheat production under two scenarios of climate change

4. DISCUSSION

We have used a statistical model to predict the yields of winter wheat as result of projected changes in weather conditions under climate change. We have not included variables that capture effects of agronomic management, such as fertilizer applications or machinery inputs. However, farmers will respond in their management decisions to perceived changes in climate parameters and adapt crop production accordingly. For example, farmers may adjust planning and harvesting dates, switch to better adapted crops, change amount of fertilizer applications, alter soil management, or invest into irrigation facilities. We have not included such adaptation measures because our aim was to single out, *ceteris paribus*, the climate change effect on winter wheat. Moreover, including potential agronomic adaptation measures in a statistical approach of predicting future yields necessitates forecasting future agronomic practices at farm level, which is outside the scope of this report. Instead, we use recent cultivation conditions (2005-2012) and inspect how these could be affected by climate change scenarios in order to assess potential risks for crop production in the absence of adaptation.

The models also demonstrate that the spatial disaggregation based on distinct environmental boundary conditions provided nuanced region-specific lessons by improving interpretability of the model outcomes. While the nationwide model suggests a low overall sensitivity of winter wheat yields to climate change, the models that are specific to the three environmental zones reveal distinct insights with important policy implications. For example, the results demonstrate clear signals of an increasing negative impact on wheat yields in southern Ukraine, while wheat yields in the northern parts of Ukraine were found to benefit from projected climate change. The contrasting North-South effects of climate change on crop productivity is well in line with the findings from studies on Russia (Dronin and Kirilenko 2011, Alcamo et al. 2007, Schierhorn et al. 2014). Our results present the first wall-to-wall and quantitative insights on the potential effects of climate change on Ukrainian wheat production that can help assess potential benefits of adaptation and improve regionally targeted strategies to responding to the likely effects of climate change on crop production. For example, one effective strategy that aims at maintaining or increasing wheat output may be to provide the framework conditions that facilitate expansion and intensification of wheat production in northern Ukraine.

Climate change will not only induce farmers to change intermediate and capital inputs but may also lead to land-use responses. For example, the weather risk for farming may become excessive in some regions, particularly in the southern Steppe zone, where land use will likely be de-intensified or even abandoned. Moreover, farmers may switch to different crops or to improved crop varieties that are better adapted to the changing climate conditions while we have analyzed relationships for winter wheat only. Because our models were calibrated to historic data with measured inputs and plant varieties, we did not account for future technological developments in plant breeding. Research in plant breeding may result in new varieties of winter wheat that are better equipped to attain stable or higher yields under the expected changes in climate conditions. However, little research and development in terms of plant breeding is conducted by Ukrainian research institutes and private companies in the region and the development of plant cultivars that are adapted to local conditions remains a bottleneck for Ukrainian crop production.

Climate scientists are increasingly concerned about the effects of the increasing number of extreme events on crop production, in particular concerning droughts and extreme heat (Lesk et al. 2016). However, we thus far did not include heat stress because a preliminary assessment

did not reveal a strong effect of heat days on winter wheat yields, most likely because heat days are correlated with temperature in the summer growth periods. Moreover, heat stress also depends on air and soil moisture that need to be considered in the calculation of a drought index, but unfortunately such data are not available to us. We will consider the inclusion of heat stress in follow-up activities based on this report.

We were also unable to include winter stress into our models. This is unfortunate because winter stress can exert substantial damages to winter wheat when extremely low air temperatures reduce soil temperatures to levels below a threshold when wheat plants perish. Such conditions can occur especially in the absence of a sufficient snow cover that insulates the winter wheat crops. However, winter stress is difficult to assess because no wall-to-wall data are available for soil temperatures, wind speed, or snow cover. The effects of climate change on winterkill are also uncertain because, on the one hand, warmer temperature may reduce frost stress while they may, together with lower precipitation, also decrease snow cover.

5. CONCLUSIONS

Wheat production is one of the cornerstones of Ukrainian agriculture but climatic changes jeopardize wheat production in some areas of Ukraine. We have assessed the effects climate change on yields of winter wheat across all of Ukraine and separately for three distinct environmental zones of the country. The results suggest slightly positive yield effects of a warming climate in the northern Mixed Forest zone (Polesia) due to the increase of solar radiation and precipitation. In the Forest Steppe, the impacts of climate change will be modest but temperature rises by up to 2 °C will endanger wheat yields towards the south of this zone. The key concern for policy makers concerned with securing future crop output is the fertile Steppe zone where a hotter and possibly also drier climate as well as higher evapotranspiration may reduce wheat yields by up to 5.5 dt/ha until 2070. Overall, wheat production in all of Ukraine may decrease by between 6 % in a modest scenario of climate change and by more than 11 % in the scenario that follows the high emissions pathway that captures the global emissions pathway at the time of writing. Developing effective adaptation measures should therefore focus on preparing this region for the anticipated climatic changes.

Critical initiatives to adapt crop production to climate change need to include improvements in both agronomy (e.g., irrigation, increasing water productivity, minimum tillage, and crop rotations) and genotypes (development of drought-tolerant varieties). However, to develop and implement such adaptation measures, more public and private investments in research and development are urgently required. For example, capital investments into climate-smart and sustainable agricultural technologies will help to maintaining or even increasing yields levels in the face of higher temperatures and evapotranspiration. However, the moratorium on land sales, that is to date in place in Ukraine, reduces investments into the agricultural sector from both domestic and foreign sources. In the long term, policy makers and investors may also facilitate expansion and intensification of wheat production in central and northern parts of Ukraine where suitable croplands may expand in response to projected climate change.

Our analysis captures statistical associations between yields and weather inputs. We therefore capture the effects of climate change on yields *ceteris paribus*, that is without accounting for potential adaptation measures, such as temporal changes in crop management, new plant varieties, irrigation, or other technological progress. This is a first step that calls for more holistic and encompassing analyses of the relationships between agriculture and climate change in Ukraine. We hope that this report can stimulate discussion and more research about the connections between climate change and crop productivity in Ukraine. Moreover, the results are also relevant for neighboring regions in the southern part of European Russia that have similar environmental conditions as the Steppe zone in Ukraine, and thus face similar challenges related to future climate change. Such discussions are not only of scientific value but also merit wider attention because of the global importance of grain production in the Eurasian steppes. Therefore, improved empirical evidence in coping with the challenges of climate change in Ukraine is of great importance also for the international community to ensure continuous supply of grain production to world markets.

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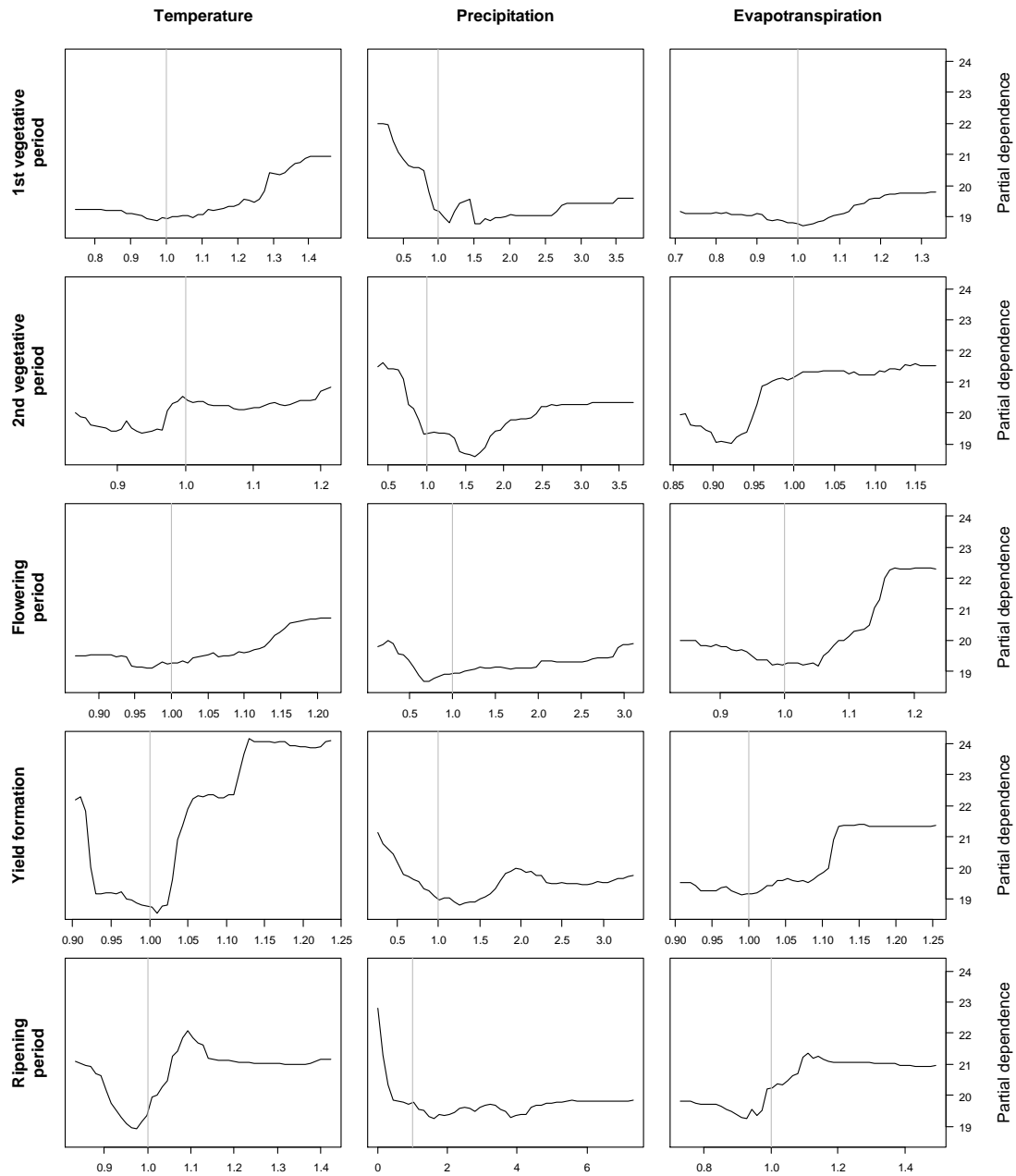50. Zastavniy, F. 1994. *Geography of Ukraine.* Lviv: Svit.

Figure A 1: Predicted climate change by growing period, 2010 to 2070
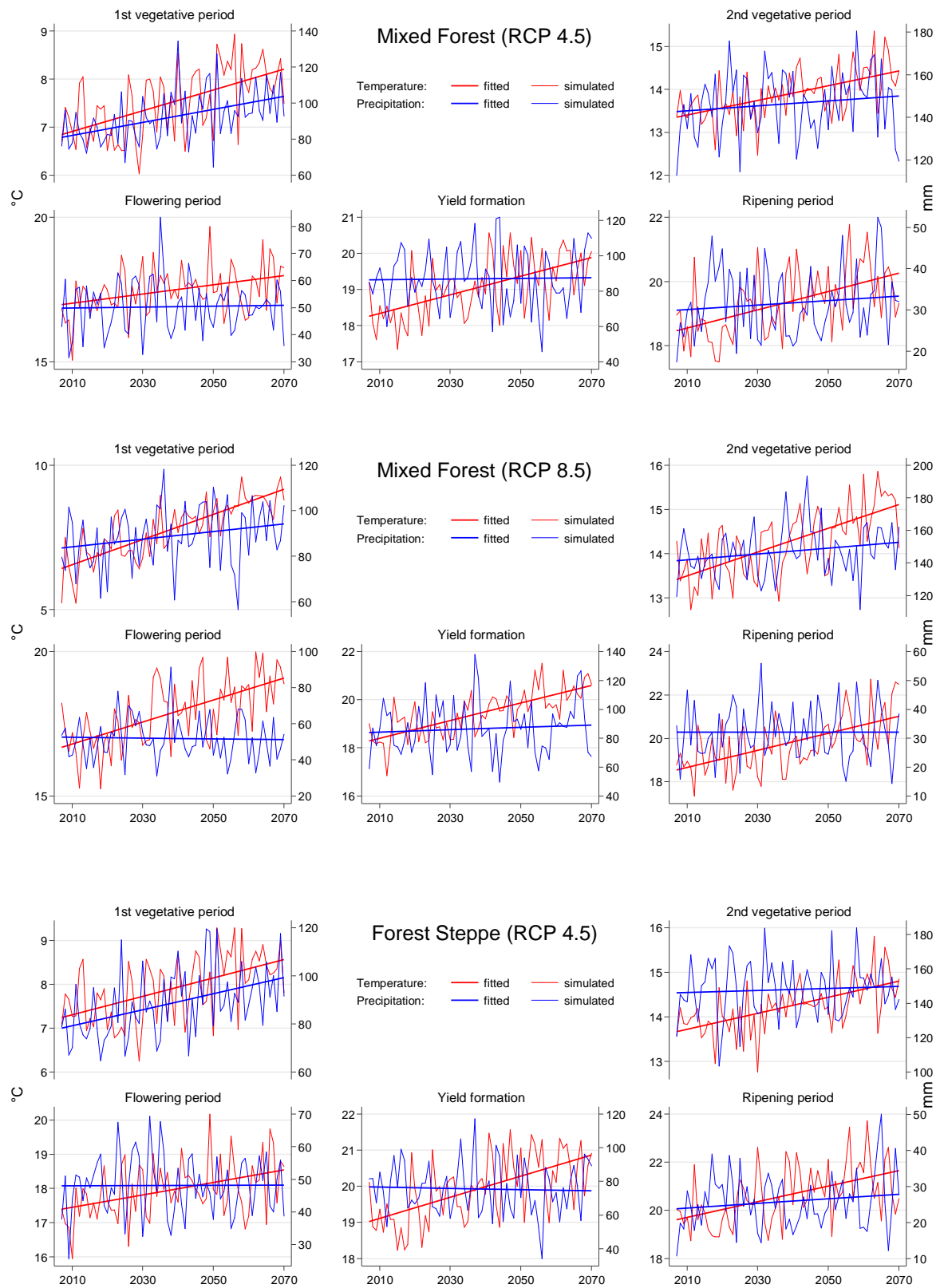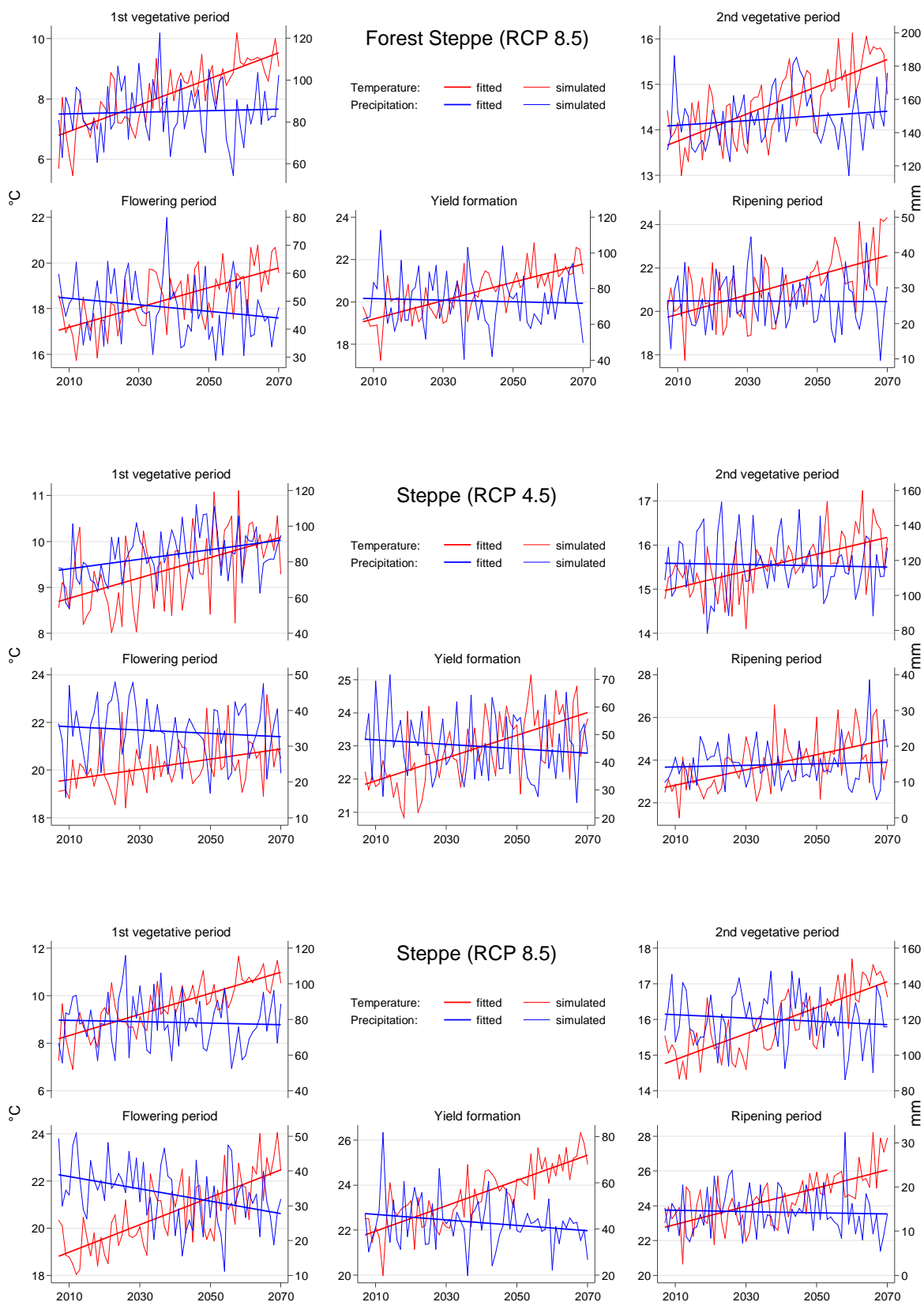
Note: All climate data were aggregated within the growing periods (Table 1), for each zone and each future concentration pathway; thick lines indicate linear fit.

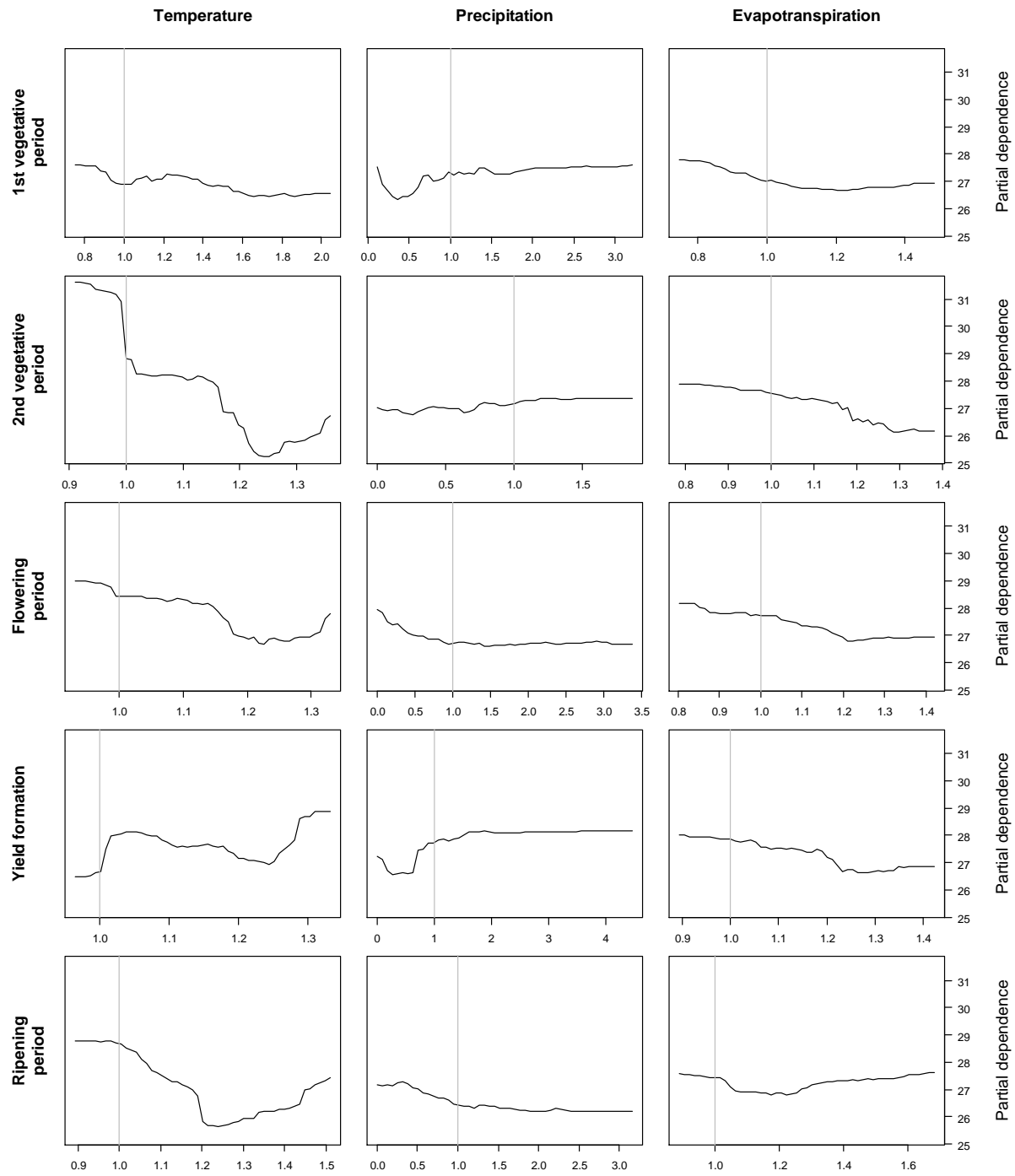**Figure A 2: Partial dependence plots: Mixed Forest zone**

Note: All climate data were normalized to respective growth period conditions from 1976 to 2005 and all models were calculated with the normalized data. For this reason, the ranges depicted on the x-axis show the deviations from the mean, i.e., from one.

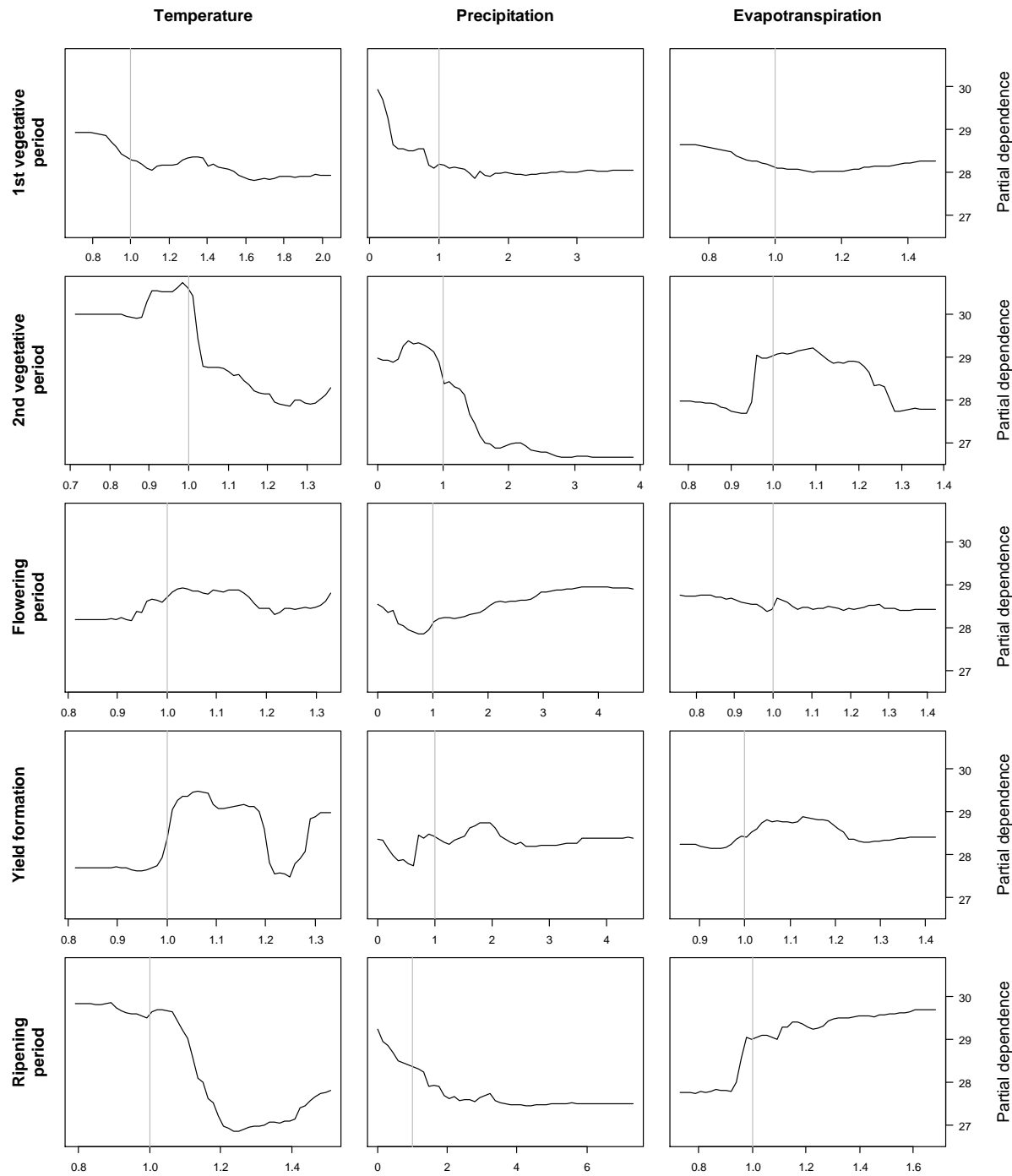# Figure A 3: Partial dependence plots: Forest Steppe zone
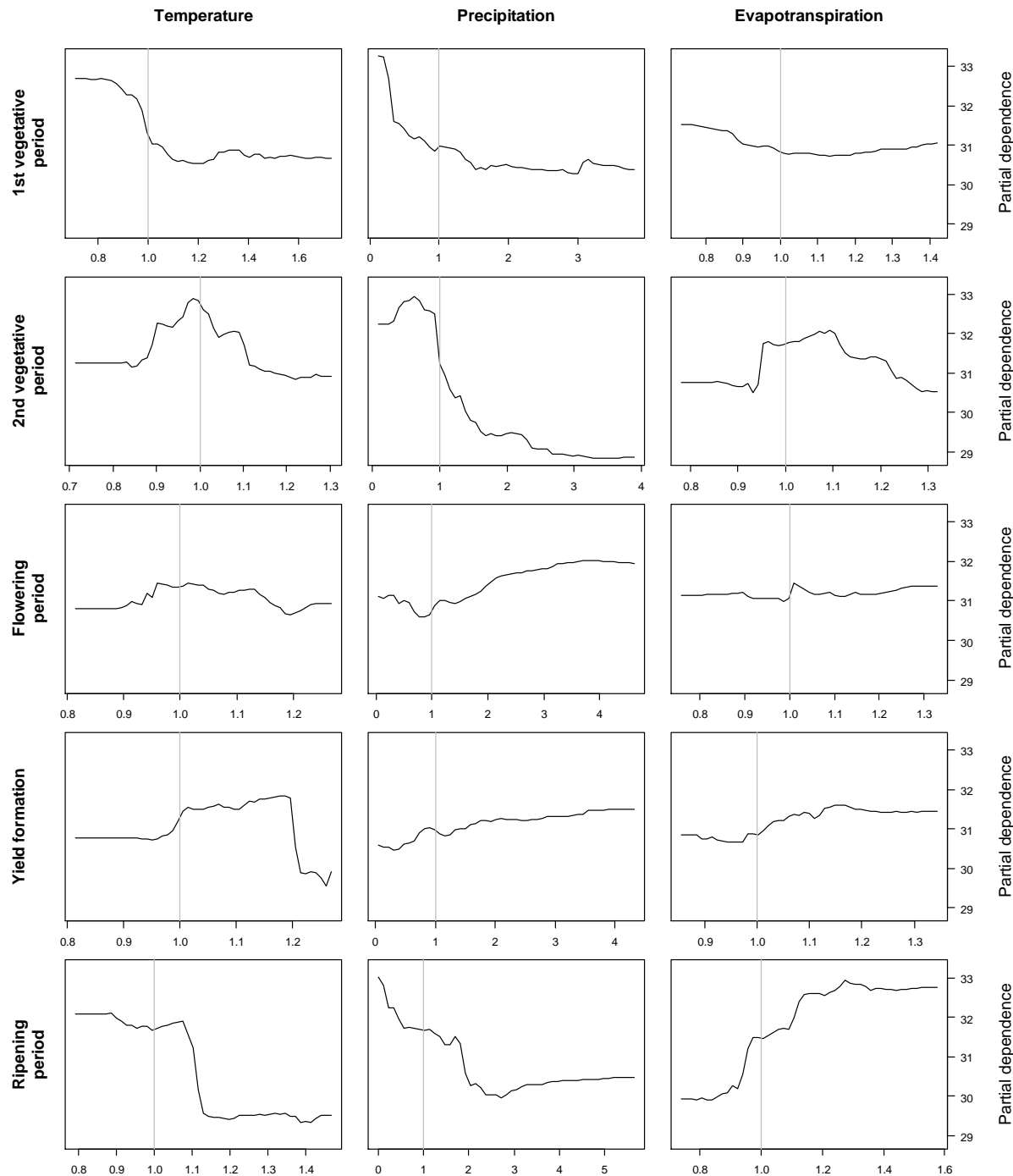
Note: See explanatory notes for Figure A 2.
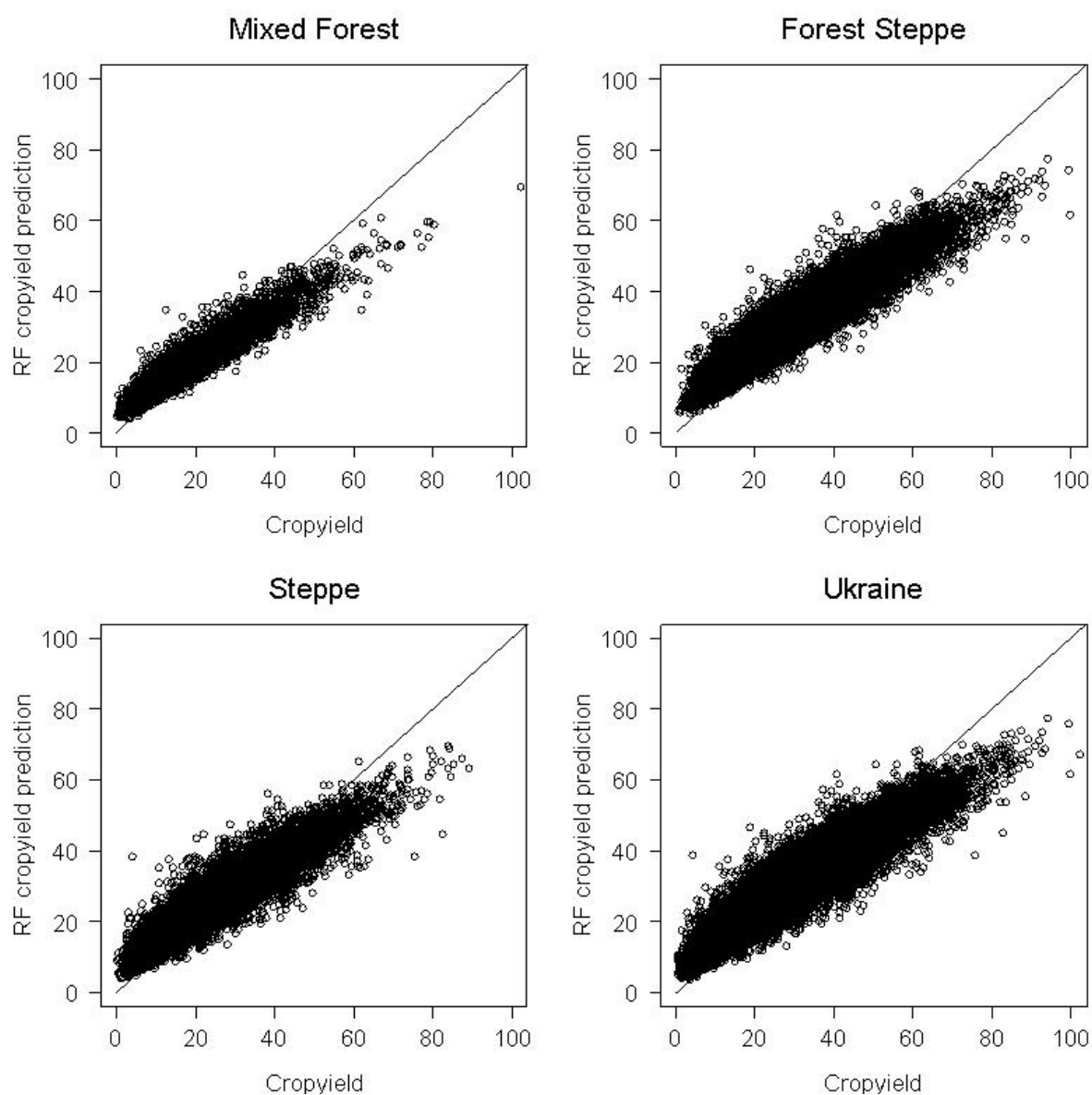
Figure A 4: Partial dependence plots: Steppe zone

Note: See explanatory notes for Figure A 2.

Figure A 5: Partial dependence plots: Ukraine

Note: See explanatory notes for Figure A 2.

Figure A 6: Model validation

Note: All observed and predicted wheat yields are measured in dt/ha; RF = random forest.

Table A 1: Model characteristics

Model	Range of calibration data (dt/ha)	Explained variance (R^2)	Mean squared error (MSE)
Mixed Forest	0.20 – 102.45	25.6 %	100.25
Forest Steppe	0.77 – 126.99	33.2 %	117.11
Steppe	0.29 – 89.62	32.1 %	88.78
Ukraine	0.20 - 126.99	37.2 %	103.66