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Supplement of

Effects of climate change in European croplands and grasslands: productivity, greenhouse gas balance and soil carbon storage

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S.1 Soil parameter calculation

The elementary data for each simulation unit obtained from the European Soil Database (ESDB; Hiederer, 2013), were used to calculate the specific input parameters for CERES-EGC and PaSim models. Both models require the saturated hydraulic conductivity (cm day^{-1}) and the hydraulic parameters (m^3 m^{-3}; calculated following Wösten et al., 1999), as well as the initialisation of carbon and nitrogen pools. More specifically CERES-EGC requires soil albedo (-; Jones and Kiniry, 1986), topsoil evaporation parameters (mm; Ritchie, 1972), soil thermal conductivity (J cm^{-1} K^{-1} day^{-1}; Hoffmann et al., 1993), the parameters of the water retention curve (Driessen, 1986; Wösten et al., 1999), the root resistance parameter (-; Jones and Kiniry, 1986) and the soil calcium carbonate (function pH values of topsoil). PaSim requires the slope of the soil moisture, the air entry potential (Campbell, 1974), and the relative root dry matter in different soil layers (function of layer depth).

S.2 Fractioning of nitrogen fertiliser application

Nitrogen amount per each crop and year (kg N ha^{-1} y^{-1}) was defined as the average amounts designed for that crop in the most frequent succession in the simulation unit. Fertiliser time distribution and fractionation were established based on crop type and the sowing date, total nitrogen amount and mineral to organic repartition. For all the crops organic N amount was supplied 5 days before the sowing date to a soil depth of 10 cm, whereas mineral N fertiliser was applied at 2 cm depth as a function of the total nitrogen amount. If the organic N amount was greater than a fixed threshold of 50 kg N ha^{-1}, mineral N was applied respectively 75 or 120 days after the sowing as a function of the crop seeding period (spring or winter crops). On the other hand, if the organic N amount was lower than 50 kg ha^{-1} and the mineral N greater than 50 kg N ha^{-1}, a third of the amount was applied at the sowing date and two third respectively 75 or 120 days after sowing, as a function of the crop sowing period. Finally, if both mineral and organic fertiliser amounts were lower than the fixed N threshold, all mineral N fraction was applied at the sowing date.

S.3 Grassland productions in EU

Low production for grasslands were observed for the Alpine area, with an average of 3.16 t DM ha^{-1} y^{-1} (max 6.67 t DM ha^{-1} y^{-1}) and for the Mediterranean regions (Greece, the southern regions of France, Italy, Portugal and Spain, including central regions of Italy and Spain) with an average of 4.34 t DM ha^{-1} y^{-1} (max 9.24 t DM ha^{-1} y^{-1}). Higher values of 7.5 t DM ha^{-1} y^{-1} (max 15 t DM ha^{-1} y^{-1}) were observed for the Atlantic area (Denmark, Netherland, Belgium, Luxembourg, northern Germany, Ireland, UK, France, Spain and northern Portugal), while the Boreal and Nemoral areas (Sweden and Finland, Lithuania, Latvia and Estonia) have an average of 6.12 t DM ha^{-1} y^{-1} (max 8.67 t DM ha^{-1} y^{-1}). The continental region (central-southern and eastern Germany, Czech Republic, Slovakia, northern Austria, Poland, Romania, Bulgaria and part of central-eastern France) scored an average production of 4.92 t DM ha^{-1} y^{-1} (max 11 t DM ha^{-1} y^{-1}); Fig. S1.

Compared to Smit et al. (2008), a slight underestimation of the productions (-15 %; 8 % of the surface) is reported for the Atlantic North zone (10 % of the surface). Chang et al. (2015a) reported the same divergences for this area in the simulation of the grassland productivity over Europe. Other Authors reported an overestimation of the Mediterranean area (e.g. van Oijen et al., 2014, Chang et al., 2015a; Chang et al., 2015b, Chang et al., 2017; Blanke et al., 2018). As reported by these Authors, divergences are explicable by the fact that ecosystem models calculate potential (maximum) productions, whereas statistics productivities are based on real harvest data. Furthermore, local low productions can be related to the lack of irrigation which is widespread e.g. in the Atlantic North region (Wriedt et al., 2009).

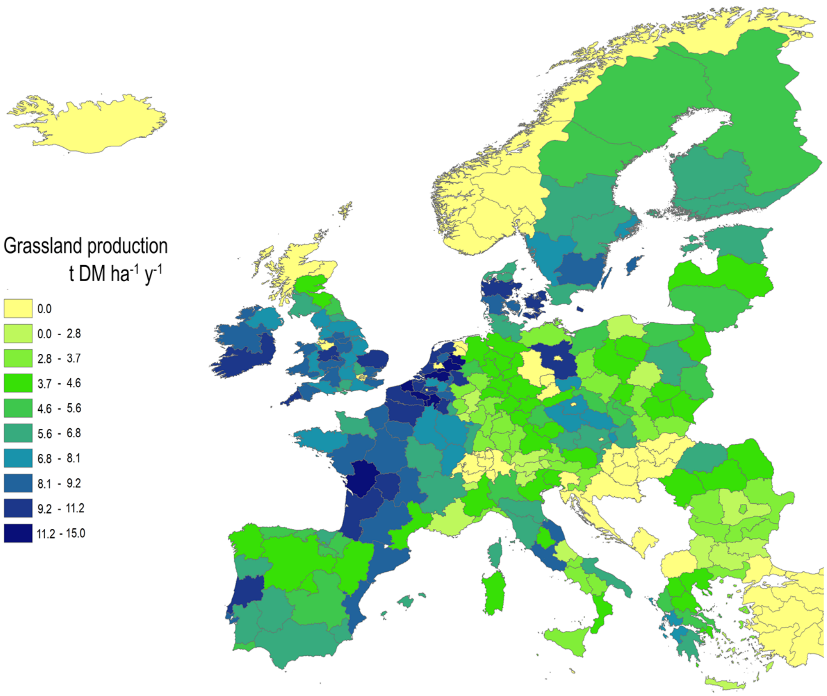


Fig. S1. Simulated grassland productions over Europe with PaSim model in the period 1978-2004, reported at NUTS2 level. Production (t DM ha^{-1} y^{-1}) are the sum of livestock intake and mowing.

S.4 CO_2 fertilisation

The effect of the increases in atmospheric CO2 was not implemented in CERES-EGC model, whereas is considered in the PaSim model. Kimball (2016) reported a potential increase of crop yields for C3 species to +19 % at 550 ppm, a concentration close to the maximum reached in RCP4.5 scenario (538.35 ppm). Similarly, for CO_2 concentrations close to the maximum reached in RCP8.5 (935 ppm) a further increase of production is forecasted by Tubiello et al. (2007). However, no effects are expected for C4 plants, as maize (Allen et al., 1990). In reality, crop yield increases can be offset by a downregulation of photosynthetic capacity (Long et al., 2004). Similarly, grasslands dominated by C3 species benefit from the rise in CO_2 concentration, whereas C4 species can be favoured only by the rise of air temperatures (Morgan et al., 2011). Thus, PaSim model is able to counterbalance the production decreases due to adverse climatic conditions with the positive effect of rising CO_2 expected during the climatic projections. This can explain the low correlation with production and air temperatures. Additionally, growing CO_2 concentrations reduces plant evapotranspiration and contributing to increase productions in waterlimited environments (Kimball, 2016). Crop models used for impact assessment have different formalism to simulate CO_2 effects, from a simple correction of final biomass produced to more complex methods (Tubiello and Ewert, 2002). Besides, all these models still needing a strength comparison with reliable experiment with elevated CO_2 and temperatures (Ainsworth et al., 2008).

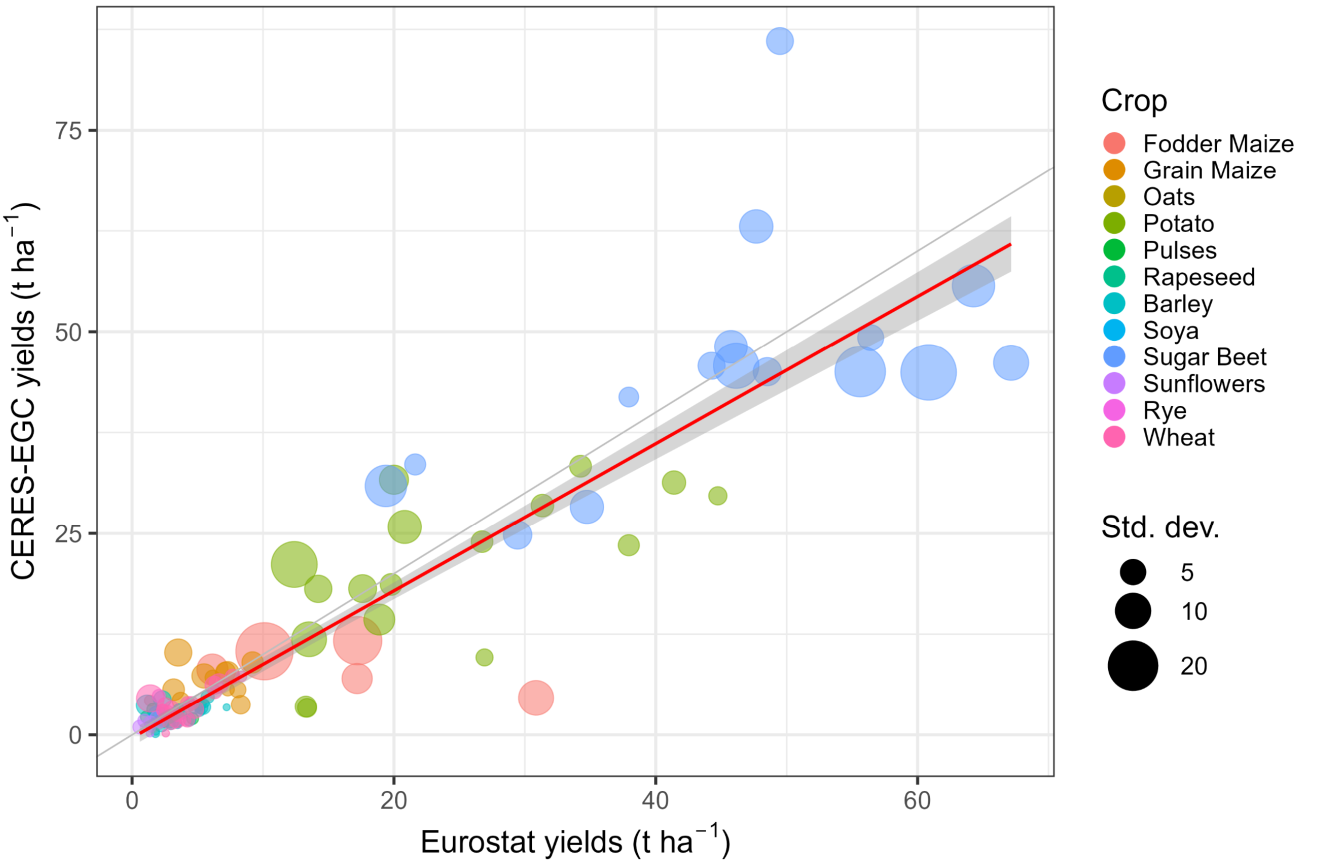


Fig S2. Comparison between simulated (CERES-EGC) and statistics (Eurostat) yields for the simulated crops in the 1978-2004 period. Each point represents the average 1978-2004 aggregated by country (NUTS0 level) and by crop type. Red line is the regression over the plotted points. $R^2 = 0.92$; $p < 0.01$.

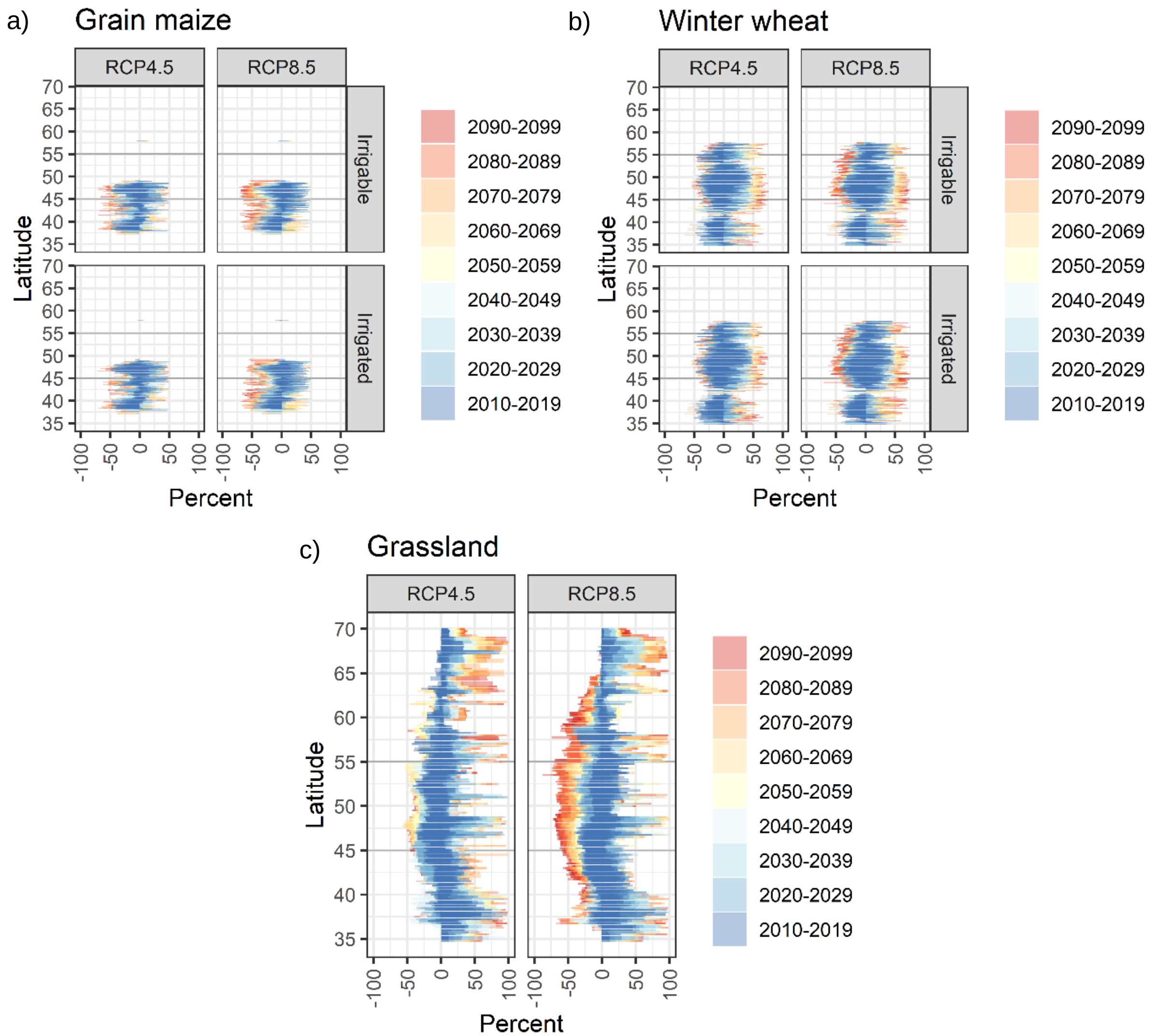
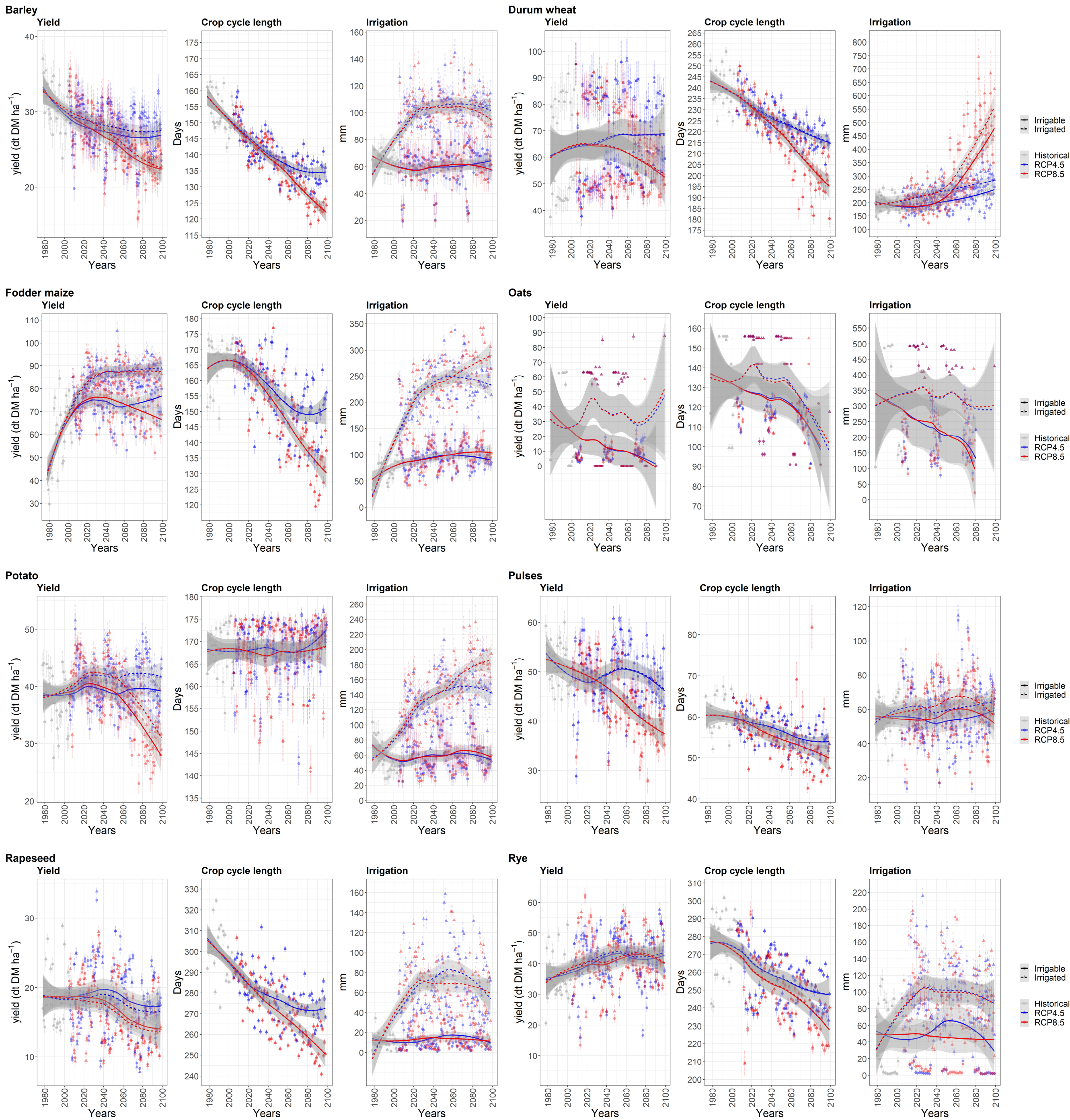


Fig S3. Relative productions compared to the historical period (1978-2004). a) Grain maize; b) Winter soft wheat; c) Grasslands. Grassland productivity is the sum of animal intake and mowing.



Barley
Yield
Crop cycle length
Irrigation
Durum wheat
Yield
Crop cycle length
Irrigation
Fodder maize
Yield
Crop cycle length
Irrigation
Oats
Yield
Crop cycle length
Irrigation
Potato
Yield
Crop cycle length
Irrigation
Pulses
Yield
Crop cycle length
Irrigation
Rapeseed
Yield
Crop cycle length
Irrigation
Rye
Yield
Crop cycle length
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yield (dt DM ha^{-1})
Days
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Years
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Historical
RCP4.5
RCP8.5

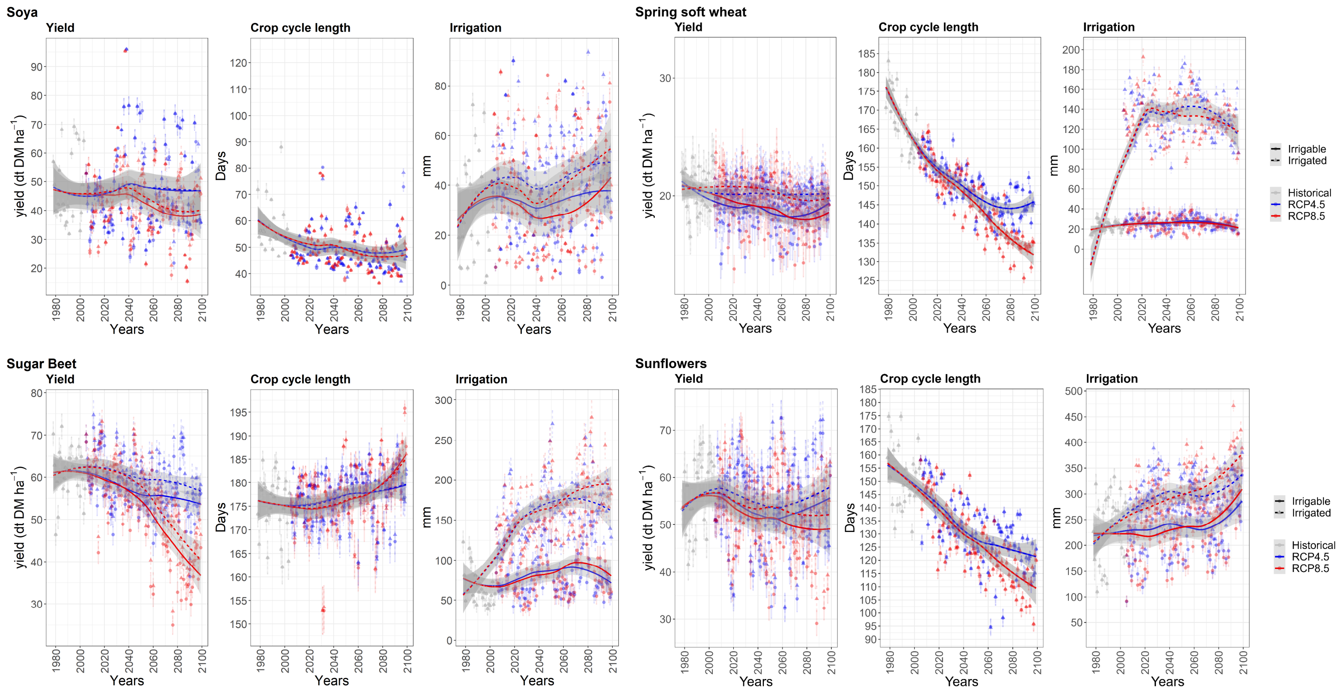

Fig. S4. Productions, length of the cropping season and irrigation needed for crops in the period 1978-2099 for the RCP4.5 and RCP8.5 climatic scenarios (blue and red colours, respectively) and with irrigable and automatic irrigation (solid and dashed lines, respectively); winter wheat and grain maize are reported in the Fig. 4.

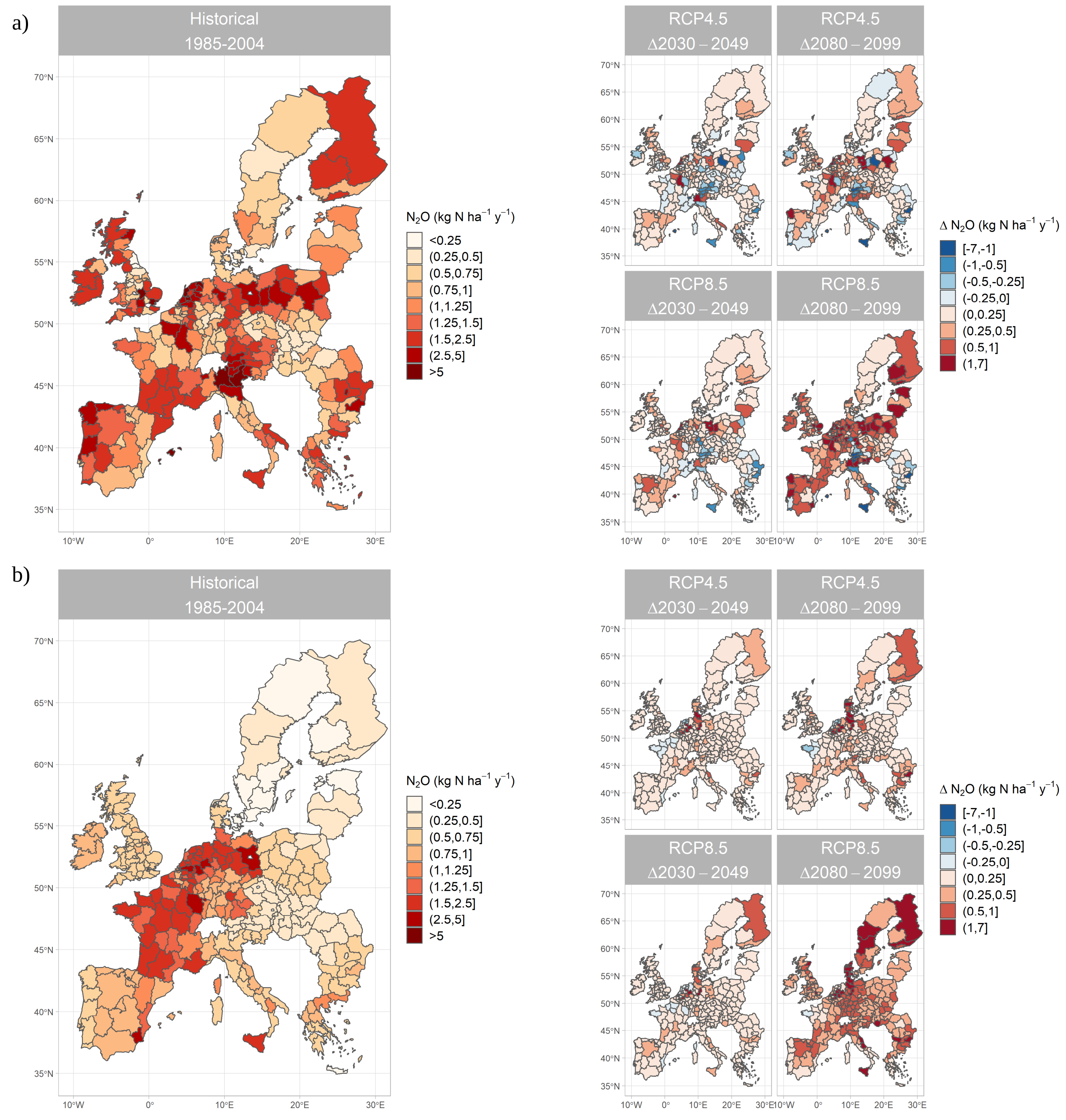

Fig S5. N_2O emissions (kg N ha^{-1} y^{-1}) for croplands (a) and grasslands (b) in the European administrative regions (NUTS2). Emissions are reported for the historical period (1985-2004), and the difference "Δ" from the middle (2030-2049) and the end (2075-2094) of the century for the two climatic scenarios RCP4.5 and RCP8.5. N_2O emissions are reported for cropland with the irrigable scenario.

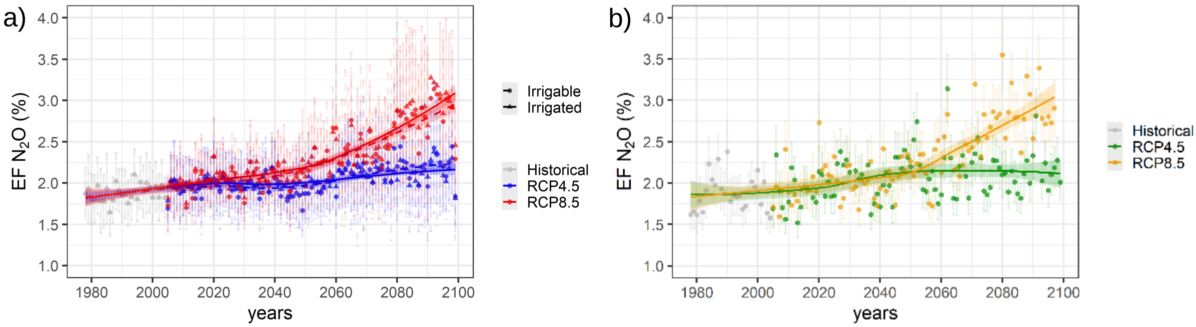

Fig S6. Emission factor, or the ratio between the N emitted as N_2O and the N introduced into the system as fertiliser (not counting for the indirect emissions and nitrogen fixation) for croplands (a) and grasslands (b) in the historical period (1978-2004) and for the RCP4.5 and RCP8.5 scenarios. Croplands consider two irrigation conditions, following the irrigable agricultural area in Europe or extending the irrigation to all the arable lands (i_RCP4.5 and i_RCP8.5).

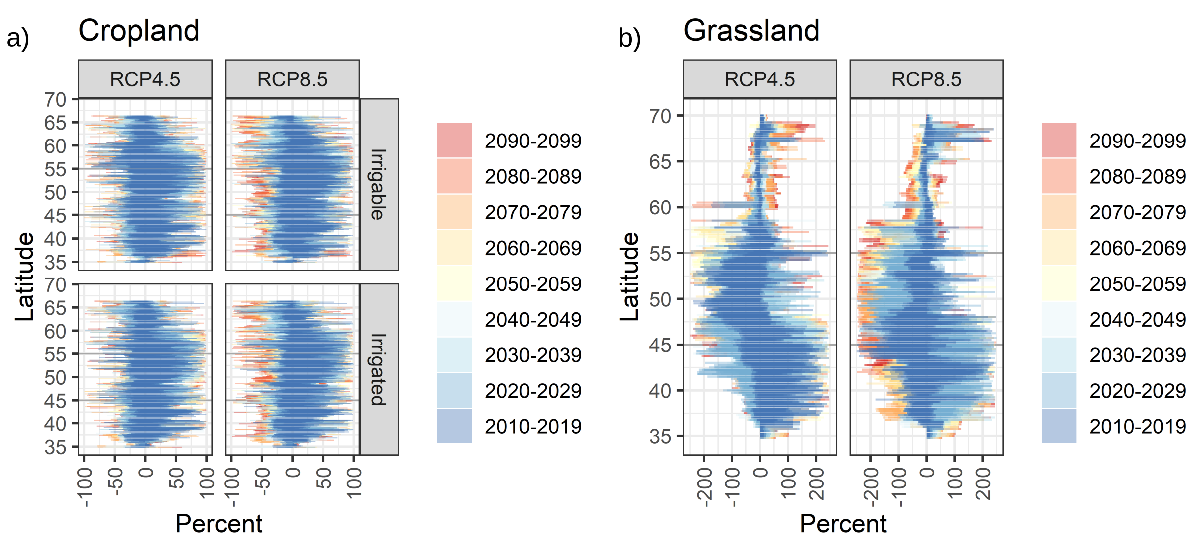

Fig S7. Relative Net ecosystem production (NEP) compared to the historical period (1978-2004). a) Croplands; b) Grasslands. X-axis reports the percentage of difference.

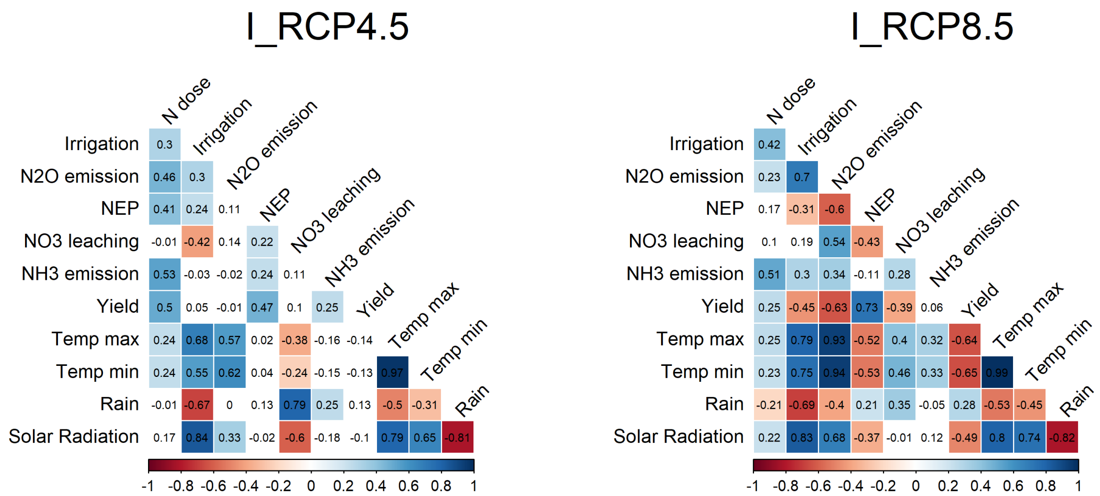

Fig S8. Correlation matrixes for croplands considering the most interesting indicators for the objective of this study. Correlation is presented for croplands for the irrigated scenarios i_RCP4.5 and i_RCP8.5 scenarios. Coloured squares means significant results (p-value < 0.05).

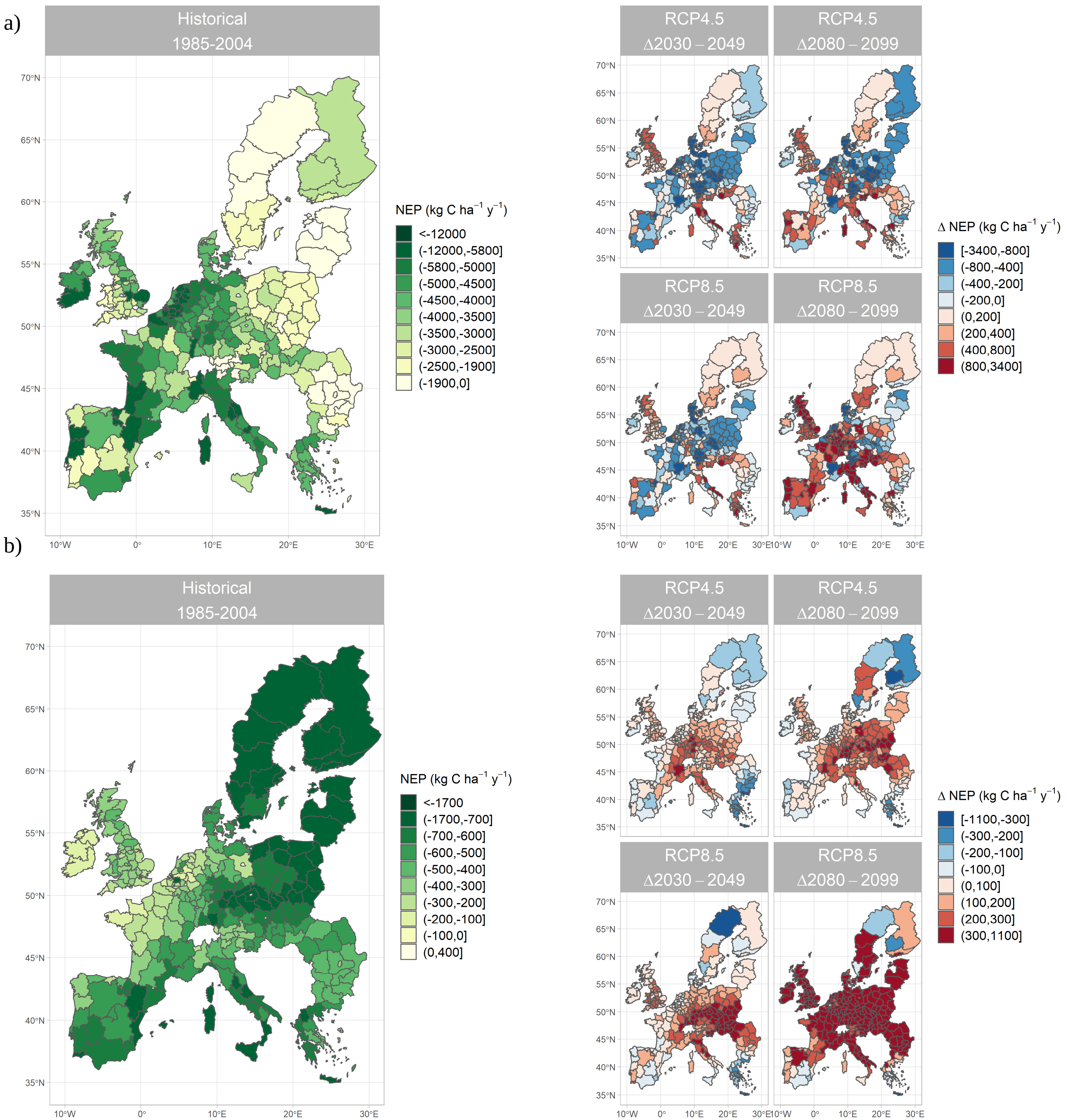

Fig S9. NEP (kg C ha^{-1} y^{-1}) for croplands (a) and grasslands (b) in the European administrative borders (NUTS2). Emissions are reported for the historical period (1985-2004), and the difference "Δ" from the middle (2030-2049) and the end (2075-2094) of the century for the two climatic scenarios RCP4.5 and RCP8.5. NEP is reported in cropland with the irrigable scenario.

Table S1: Crop and grassland productivity (t DM ha^{-1} y^{-1}) and NEP (Net Ecosystem Productivity; kg C-CO_2 ha^{-1} y^{-1}) in Europe reported by latitude gradients (low, mid, high) during the historical and the two climate change scenarios (RCP4.5 and RCP8.5), and with irrigation scenarios (*i_RCP4.5* and *i_RCP8.5*).

Scenario	Land use	**Productivity** (t DM ha^{-1} y^{-1})			**NEP** (kg C-CO_2 ha^{-1} y^{-1})		
		low latitude (<= 45°)	**mid latitude** (>45° - <=55°)	**high latitude** (> 55°)	**low latitude** (<= 45°)	**mid latitude** (>45° - <=55°)	**high latitude** (> 55°)
Period 1978-2004							
Historic	Grassland	4.58	6.00	5.80	-631	-450	-960
	Cropland	6.87	5.15	3.69	-4359	-3867	-2180
Period 2030-2049							
RCP4.5	Grassland	4.87	5.67	6.51	-587	-366	-976
	Cropland	6.69	5.43	4.14	-4508	-4239	-2259
i_RCP4.5	Cropland	6.88	5.76	4.26	-4125	-4076	-2145
RCP 8.5	Grassland	4.91	5.70	6.67	-549	-226	-975
	Cropland	6.74	5.38	3.97	-4471	-4215	-2177
i_RCP8.5	Cropland	6.89	5.68	4.15	-4093	-4028	-2051
Period 2080-2099							
RCP4.5	Grassland	5.06	5.67	7.08	-532	-310	-987
	Cropland	6.63	5.29	4.22	-4332	-4175	-2321
i_RCP4.5	Cropland	6.83	5.71	4.34	-3896	-3980	-2235
RCP8.5	Grassland	4.62	4.56	6.56	-398	36	-658
	Cropland	6.10	4.74	4.12	-4006	-3738	-2069
i_RCP8.5	Cropland	6.19	5.38	4.30	-3632	-3469	-1990

Table S2: Grain maize and winter soft wheat yields (t DM ha^{-1} y^{-1}) in EU reported by latitude gradients (low, mid, high) during the historical and two climate change scenarios.

Scenario	Land use	**Productivity** (t DM ha^{-1} y^{-1}) low latitude (<= 45°)	mid latitude (>45° to <=55°)	high latitude (> 55°)
Period 1978-2004				
Historic	Grain Maize	8.91	6.14	-
	Winter Soft Wheat	6.22	4.80	3.86
Period 2030-2049				
RCP4.5	Grain Maize	8.41	6.73	-
	Winter Soft Wheat	5.98	5.16	3.39
i_RCP4.5	Grain Maize	9.04	7.30	-
	Winter Soft Wheat	6.06	5.10	3.37
RCP 8.5	Grain Maize	8.83	6.72	-
	Winter Soft Wheat	5.95	4.93	3.13
i_RCP8.5	Grain Maize	9.61	7.20	-
	Winter Soft Wheat	6.06	4.86	3.12
Period 2080-2099				
RCP4.5	Grain Maize	7.90	6.49	-
	Winter Soft Wheat	6.47	4.63	6.33
i_RCP4.5	Grain Maize	8.87	7.38	-
	Winter Soft Wheat	6.59	4.58	6.16
RCP8.5	Grain Maize	7.46	4.97	-
	Winter Soft Wheat	6.33	4.20	5.38
i_RCP8.5	Grain Maize	8.29	6.41	-
	Winter Soft Wheat	6.48	4.10	5.40

Table S3. Statistics of the simulated crop yields compared with Eurostat for the period 1978-2004. Yields are reported as standard humidity.

Crop	MAE	RMSE	RRMSE	Minimum t DM ha^{-1}		Maximum t DM ha^{-1}		Mean t DM ha^{-1}	
	t DM ha^{-1}	t DM ha^{-1}	%	**Simulated**	**Statistics**	**Simulated**	**Statistics**	**Simulated**	**Statistics**
Fodder Maize	2.21	2.97	27.1	5.41	5.54	15.37	15.09	10.66	10.95
Grain Maize	1.58	1.77	31.8	5.44	4.61	8.76	6.66	7.15	5.56
Oats	0.496	0.648	22.1	1.94	2.57	4.35	3.30	3.24	2.93
Potato	3.3	4.04	19.2	13.14	18.59	21.10	24.00	17.93	21.06
Pulses	0.387	0.462	18.2	1.90	2.18	2.58	3.01	2.21	2.54
Rapeseed	0.423	0.495	23.4	1.38	1.85	2.89	2.56	1.89	2.12
Barley	0.543	0.625	17.6	2.38	3.09	3.71	4.09	3.10	3.55
Soya	0.467	0.621	35	1.37	1.52	2.97	2.16	2.05	1.79
Sugar Beet	4.35	5.29	12.8	30.94	36.99	48.03	48.93	40.74	41.39
Sunflowers	0.348	0.405	24.9	1.38	1.42	2.24	1.96	1.89	1.63
Rye	0.852	1.09	38.6	2.06	2.46	5.27	3.41	3.57	2.83
Wheat	0.894	1.05	25	3.59	3.47	6.16	4.83	5.02	4.21

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