



Cereal yield gaps across Europe

René Schils^{a,*}, Jørgen E. Olesen^b, Kurt-Christian Kersebaum^c, Bert Rijk^a, Michael Oberforster^d, Valery Kalyada^e, Maksim Khitrykau^e, Anne Gobin^f, Hristofor Kirchev^g, Vanya Manolova^g, Ivan Manolov^g, Mirek Trnka^{h,i}, Petr Hlavinkaⁱ, Taru Palosuo^j, Pirjo Peltonen-Sainio^j, Lauri Jauhiainen^j, Josiane Lorgeou^k, H el ene Marrou^l, Nikos Danalatos^m, Sotirios Archontoulisⁿ, N andor Fodor^o, John Spink^p, Pier Paolo Roggero^q, Simona Bassu^q, Antonio Pulina^q, Till Seehusen^r, Anne Kjersti Uhlen^r, Katarzyna  zyłowska^s, Anna Nier bca^s, Jerzy Kozyra^s, Jo o Vasco Silva^a, Benvindo Martins Ma c as^t, Jos e Coutinho^t, Viorel Ion^u, Jozef Tak c v, M. In s M nguez^w, Henrik Eckersten^x, Lilia Levy^y, Juan Manuel Herrera^y, J rg Hiltbrunner^y, Oleksii Kryvobok^z, Oleksandr Kryvoshein^z, Roger Sylvester-Bradley[ ], Daniel Kindred[ ], Cairistiona F.E. Topp[ ], Hendrik Boogaard[ ], Hugo de Groot[ ], Jan Peter Lesschen[ ], Lenny van Bussel[ ], Joost Wolf[ ], Mink Zijlstra[ ], Marloes P. van Loon[ ], Martin K. van Ittersum[ ]

^a Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, The Netherlands

^b Department of Agroecology, Aarhus University, Blichers All  20, Tjele, DK, 8830, Denmark

^c Research Platform Models and Simulation, ZALF, Leibniz-Centre for Agricultural Landscape Research, Eberswalder Str. 84, 15374, Muencheberg, Germany

^d Austrian Agency for Health and Food Safety (AGES), Institute for Sustainable Plant Production, Spargelfeldstrasse 191, 1220, Vienna, Austria

^e Centre for Climate Research, Institute for Nature Management of National Academy of Sciences of Belarus, F. Skoriny Str. 10, 220114, Minsk, Belarus

^f Flemish Institute for Technological Research (VITO), Boeretang 200, 2400, Mol, Belgium

^g Crop Science Department, Faculty of Agronomy, Agricultural University, 12 Mendeleev str., 4000, Plovdiv, Bulgaria

^h Institute of Agrosystems and Bioclimatology, Mendel University in Brno, Zem delsk  1, 613 00, Brno, Czech Republic

ⁱ Global Change Research Institute of the Czech Academy of Sciences, B lidla 986/4a, 603 00, Brno, Czech Republic

^j Natural Resources Institute Finland (Luke), Latokartanonkaari 9, FI-00790, Helsinki, Finland

^k ARVALIS-Institut du v g tal, 91720, Boigneville, France

^l UMR SYSTEM, Montpellier SupAgro, INRA, CIRAD, IAMM, Universit  de Montpellier, Montpellier, France

^m Department of Agriculture Crop Production and Rural Environment, School of Agricultural Sciences, University of Thessaly, Fytokoy Str, 384 46, N.Ionia, Magnisia, Greece

ⁿ Department of Agronomy, Iowa State University, 1216 Agronomy Hall, Ames, IA, 50011, USA

^o Agricultural Institute, Centre for Agricultural Research, Hungarian Academy of Sciences, 2462, Martonv s r, Brunsvik u. 2., Hungary

^p Teagasc Crops, Environment and Land Use Programme, Oak Park Crops Research Centre, Carlow, Ireland

^q Department of Agricultural Sciences and Desertification Research Centre – NRD, University of Sassari, Viale Italia 39, 07100, Sassari, Italy

^r Norwegian Institute of Bioeconomy Research, Grain and Forage Seed Agronomy, Nylinna 226, NO-2849, Kapp, Norway

^s Institute of Soil Science and Plant Cultivation, Czartoryski 8 Street, 24-100, Pulawy, Poland

^t National Institute of Agrarian and Veterinary Research, Plant Breeding Station, Estrada de Gil Vaz, Apartado 6, 7351-901 Elvas, Portugal

^u Faculty of Agriculture - Plant Science Department, University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd, 011464, Bucharest-1, Romania

^v National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Ga arinova 10, 827 13, Bratislava, Slovakia

^w Department of Agricultural Production, CEIGRAM, Technical University of Madrid, Spain

^x Department of Crop Production Ecology, Swedish University of Agricultural Sciences, P.O. Box 7043, SE-75007, Uppsala, Sweden

^y Research Group Varieties and Production Techniques, Plants and Plant Products Competence Division, Agroscope, Route de Duillier 50, 1260, Nyon, Switzerland

^z Ukrainian Hydrometeorological Institute, 37 Nauki Street 03028, Kiev, Ukraine

[ ] ADAS, Battlegate Road, Boxworth, Cambridge, CB23 4 NN, United Kingdom

[ ] SRUC, West Mains Road, Edinburgh, EH9 3JG, United Kingdom

[ ] Team Earth Observation and Environmental Informatics, Wageningen Environmental Research, P.O. box 47, 6700 AA, Wageningen, The Netherlands

[ ] Team Sustainable Soil Use, Wageningen Environmental Research, P.O. box 47, 6700 AA, Wageningen, The Netherlands

ARTICLE INFO

Keywords:

Wheat
Barley

ABSTRACT

Europe accounts for around 20% of the global cereal production and is a net exporter of ca. 15% of that production. Increasing global demand for cereals justifies questions as to where and by how much Europe's

* Corresponding author.

E-mail address: rene.schils@wur.nl (R. Schils).

<https://doi.org/10.1016/j.eja.2018.09.003>

Received 5 April 2018; Received in revised form 4 September 2018; Accepted 4 September 2018

Available online 18 September 2018

1161-0301/  2018 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Grain maize
Crop modelling
Yield potential
Nitrogen

production can be increased to meet future global market demands, and how much additional nitrogen (N) crops would require. The latter is important as environmental concern and legislation are equally important as production aims in Europe. Here, we used a country-by-country, bottom-up approach to establish statistical estimates of actual grain yield, and compare these to modelled estimates of potential yields for either irrigated or rainfed conditions. In this way, we identified the yield gaps and the opportunities for increased cereal production for wheat, barley and maize, which represent 90% of the cereals grown in Europe. The combined mean annual yield gap of wheat, barley, maize was 239 Mt, or 42% of the yield potential. The national yield gaps ranged between 10 and 70%, with small gaps in many north-western European countries, and large gaps in eastern and south-western Europe. Yield gaps for rainfed and irrigated maize were consistently lower than those of wheat and barley. If the yield gaps of maize, wheat and barley would be reduced from 42% to 20% of potential yields, this would increase annual cereal production by 128 Mt (39%). Potential for higher cereal production exists predominantly in Eastern Europe, and half of Europe's potential increase is located in Ukraine, Romania and Poland. Unlocking the identified potential for production growth requires a substantial increase of the crop N uptake of 4.8 Mt. Across Europe, the average N uptake gaps, to achieve 80% of the yield potential, were 87, 77 and 43 kg N ha⁻¹ for wheat, barley and maize, respectively. Emphasis on increasing the N use efficiency is necessary to minimize the need for additional N inputs. Whether yield gap reduction is desirable and feasible is a matter of balancing Europe's role in global food security, farm economic objectives and environmental targets.

1. Introduction

Cereals are grown on half of the European Union's (EU) farms, occupying a third of EU's agricultural area and accounting for a quarter of its crop production value (EU, 2014). On a global scale, Europe accounts for 20% of the total cereal production, of which about 63% is produced in the countries of the EU28 (FAO, 2016). Cereals in the EU28 are mainly used for animal feed (61%) and human consumption (24%), while smaller other purposes include alcoholic beverages (5%), bio-energy (4%) and seeds (3%) (EU, 2016). Wheat and rye are used almost equally for animal feed and human consumption, while barley, maize, sorghum, oats and triticale are predominantly used for animal feed. In recent years, Europe has been a net exporter of around 15% of its cereal production (FAO Food Outlook, 2016). The exported cereals are mainly wheat and barley, while the imports consist mainly of maize.

Over the coming decades the global demand for agricultural products, including cereals, is expected to rise, driven by population and income growth (Alexandratos and Bruinsma, 2012; Godfray and Garnett, 2014). The rising role of crop products in the transition towards low-fossil-carbon economies (Gabrielle et al., 2014) will put further pressure on agricultural production. As suitable agricultural land for expansion of agricultural production is becoming scarce (Lambin and Meyfroidt, 2011) and expanding the agricultural area comes with substantial environmental trade-offs, sustainable production increases from intensifying the use of existing agricultural land will be the main avenue to satisfy the increasing demand. Sustainable intensification, i.e. realising high yields on existing croplands with efficient resource use is important to meet global crop demand with minimal environmental impacts (Tilman et al., 2011). Avoiding food loss and waste, and reducing consumption of livestock products (Garnett et al., 2013) are also important, but are not further considered in this paper.

Projections by the Food and Agricultural Organization (Alexandratos and Bruinsma, 2012) show that the global annual demand for cereals, including both food and non-food use, will increase from 2.1 Gt in the base years around 2006 to 3.0 Gt by 2050. Almost all the increases in the consumption of cereals will come from developing countries, particularly after 2020 when the use of cereals for biofuels is assumed to peak at 180 Mt. Developing countries are projected to continue increasing their net imports of cereals from the rest of the world. Moreover, if intensification is not successful in developing countries, these regions will increasingly depend on imports of cereals (Van Ittersum et al., 2016b), and traditional exporters such as Europe may sustain or even increase their share in the growing global grain trade. Consequently, the question “where and by how much can Europe's production be enhanced to meet future cereal demand?” is justified. Gain in cereal yields will at least partly rely on increased nitrogen

(N) and other inputs (Dobermann and Cassman, 2005). Given the importance of reactive N as a driver for many of today's local and global environmental concerns (Sutton et al., 2011; De Vries et al., 2013), it is relevant to complement the estimates of potential production increases with estimates of the associated additional N requirements.

When considering sustainable intensification in the context of European cereal production, it is essential to consider the large heterogeneity of Europe's agricultural landscape. Europe has a wide geographic extent comprising a variety of farm structures and intensities combined with pronounced differences in environmental conditions, rendering substantial variation in inputs (nutrients, pesticides, irrigation) and outputs (crop yields), as well as future yield potential. We use the concept of yield gaps (Van Ittersum et al., 2013) to identify the regions with unlocked yield potential. A yield gap is the difference between potential and actual yield. Potential yields can be calculated for irrigated (yield potential) and rainfed (water-limited yield potential) conditions. Yield potential assumes unconstrained crop growth and perfect management that avoids yield limitations from nutrient deficiencies and water stress, and yield reductions from weeds, pests and diseases. Yield potential is therefore location and year specific and depends on the crop genotype along with solar radiation and air temperature during the crop growing season. In addition, water-limited yield potential depends on water supply as dictated by precipitation and soil available water. Full yield gap closure is generally not economically feasible nor environmentally desirable (Cassman, 1999; Van Ittersum et al., 2013). We thus take 80% of the yield potential as the reference for increases that can be achieved in farming practice.

The objective of the present study is to quantify actual and potential yields for wheat, barley and maize in Europe. Together these three crops represent 90% of the European cereal production. We use a country-by-country, bottom-up approach to establish statistical estimates of actual grain yield, and compare these to modelled estimates of potential yields. In this manner, we identify the yield gaps and the associated opportunities for increased cereal production. Furthermore, we aim to quantify the additional N required to increase yields and reduce yield gaps. These results provide essential information for strategic decisions by policy makers, NGO's, agro-industry and commodity traders on topics related to market development and EU and national policies for agriculture, food security and sustainable development.

2. Material and methods

The yield gap analysis of cereals in Europe applies the approach developed and described by the Global Yield Gap Atlas (GYGA; www.yieldgap.org) project. In brief, the approach distinguishes the following main steps: (1) selection of representative climate zones (CZ) based on dominant crop areas, (2) selection of reference weather stations (RWS)

that represent the selected CZs, (3) selection of dominant soil types and cropping systems in a 100 km radius around the RWS, (4) crop model simulations to establish rainfed or irrigated yield potential, and (5) estimation of actual yields from statistical surveys. Detailed information and justification is available in separate publications on climate zones (Van Wart et al., 2013), upscaling from RWS to CZ and national scale with area-weighted averages (Van Bussel et al., 2015), and criteria for data selection (Grassini et al., 2015a). For 22 out of the 39 countries, national country agronomists were involved, representing 94% of the wheat and barley area, and 82% of the maize area. They had a pivotal role in data access, expert estimates and evaluation of results. The next sections present a point-by-point account of the underlying data and methods used for Europe.

2.1. Selected climate zones

The climate zonation (Van Wart et al., 2013), at a 5' resolution, combines three categorical variables: (1) six classes of growing degree days with a base temperature of 0 °C, (2) ten classes of an aridity index (annual total precipitation divided by annual total potential evapotranspiration), and (3) three classes of temperature seasonality (standard deviation of monthly average temperatures). On average, there are 15 CZs per country, but it varied from 2 (the Netherlands) to 48 (Spain). Harvested areas for wheat, barley and grain maize were taken from the Spatial Production Allocation Model (SPAM) of Harvestchoice (You et al., 2014), presenting harvested areas around the year 2005 at a 5' grid, which is the most recent version to date. Both layers were combined to calculate the harvested area per climate zone per country. The harvested areas of wheat (34 Mha), barley (20 Mha) and maize (13 Mha) were distributed over 80 CZs for wheat and barley, and 75 CZs for maize (Table 1).

Selection of the CZs was carried out in two steps, with the aim to cover at least 50% of the harvested area. First, all CZs with at least 5% of the national harvested area were selected. However, for some countries with many relatively small climate zones this approach resulted in a low crop area covered by the CZs. Therefore, also CZs with less than 5% of the national harvested area were selected if a suitable weather station was present for that particular CZ. The final number of selected CZs was on average 5 per country, with a range of 1 (Luxemburg) to 16 (Spain). On average, 43% of the number of CZs in a country were selected representing on average 88% of the national crop area, but area coverage ranged from 26% (Bosnia Herzegovina – maize) to 100% (the Netherlands) of the national crop area.

2.2. Reference weather stations (RWS)

Weather data were collected for stations in the selected CZs with at least ten years of consecutive daily data and less than 20% missing data for each variable. Precipitation, minimum and maximum temperature, vapour pressure and wind speed were used from stations in the NOAA Global Surface Summary of the Day (<https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00516>). If suitable weather stations with adequate data were unavailable, gridded weather data from Agri4Cast (<http://agri4cast.jrc.ec.europa.eu/>) were used. Daily radiation was derived from NASA (<http://power.larc.nasa.gov/>). For precipitation, zero was assigned to missing values, while for other variables linear interpolation was used to fill data gaps.

The total number of selected RWSs for wheat, barley and maize was 287, 271 and 202, respectively. This equates to an average of 1.3 weather stations per climate zone. In 22 cases (Albania, Bosnia Herzegovina, Kosovo, Macedonia, Moldova and Montenegro) a suitable RWS with actual weather data was unavailable, and gridded data were used that represented the location of the specific weather station.

2.3. Soils and crops

Data on water content at field capacity ($pF = 2.5$) minus water content at wilting point ($pF = 4.2$), root penetrable soil depth and hydrogeological class of soils were taken from the 1 km × 1 km grid of the European Soil Database (Panagos et al., 2012). Within the 100 km zone around each RWS, the three dominant Soil Map Units (SMUs) were selected, based on the harvested area. Each SMU comprises a varying number of Soil Type Units (STUs) of which the soil parameters were used as input to the model.

The yield gap assessment in this study covers rainfed wheat, barley and maize, as well as irrigated maize. For wheat and barley, both spring sown and autumn sown cropping systems were taken into account if they covered at least 15% of the total wheat or barley area (Table 1). Common wheat is the default wheat type, but for Mediterranean regions durum wheat was also considered. In this study the term “maize” stands for grain maize; forage maize was not included.

2.4. Crop modelling

We implemented the WOFOST crop model version 7.1.7 (Van Diepen et al., 1989; Supit et al., 1994; Boogaard et al., 1998; De Wit et al., 2018), which was calibrated for many regions throughout Europe by Boons-Prins et al. (1993) and Wolf et al. (2011). WOFOST computes daily biomass accumulation and its distribution over crop organs during the growth period using a photosynthesis minus respiration approach. Crop yield was simulated for the potential (Yp) and the water-limited (Yw) production situation. Yp is determined by temperature, day length, solar radiation and genetic characteristics assuming absence of any water or other stress factors. Yw is limited by water supply, and hence influenced by rainfall, soil type and depth. Soil water dynamics in the root zone were simulated with a daily time step. The model does not account for capillary rise of water from below the root zone. To prevent overestimation of water limitation for soils with shallow groundwater (e.g. large parts of the Netherlands and the Po valley in Italy), Yw was assumed to equal Yp in these regions. For both Yp and Yw non-limiting nutrient supply was assumed. Yield losses caused by pests, diseases, weeds or any mismanagement by farmers were considered absent for both Yp and Yw. The same holds for extreme weather events and their effects like lodging, hail or flooding, which are rarely considered in crop models and could also be caused by off-site events (Rötter et al., 2018). Vernalization was not implemented in WOFOST and crop growth and phenological development for autumn sown crops were therefore calculated from January 1st of each year onwards (Ceglar et al., 2018), assuming a fixed initial dry biomass of 210 kg ha⁻¹ (Boons-Prins et al., 1993).

The crop parameters from Boons-Prins et al. (1993) and Wolf et al. (2011) were updated in two steps to represent conditions covering approximately the last 15 to 20 years. First, additional phenology data were collected from a variety of sources, comprising either geo-referenced networks of observations, experimental sites or expert estimates by country agronomists (Supplement 1). For spring sown crops, the observations consisted of day of sowing, emergence, anthesis and maturity. For autumn sown crops, emergence was fixed on January 1st. All phenology data were grouped per country per climate zone, and subsequently temperature sums between sowing and emergence, between emergence and anthesis, and between anthesis and maturity were calculated for each RWS. Initial model runs were carried out with these data, and the simulated harvest index (HI) and maximum leaf area index (LAIM) were checked against a plausible range proposed by Wolf et al. (2011). If more than 10% of the number of simulations were outside the plausible range for HI (minimum: 0.35–0.40; maximum 0.55–0.60, depending on crop) or LAIM (minimum 3–4; maximum 6–7, depending on crop), crop parameters were adjusted within biologically plausible values as per the guidelines for regional calibration of WOFOST (Boons-Prins et al., 1993; Wolf et al., 2011). The relevant

Table 1
Harvested areas of wheat, barley and grain maize around 2005 (You et al., 2014) (a–c), cropping systems included in the analysis (d–i), including the proportion of spring sown and autumn sown wheat (d,e) and barley (f,g), the total number of climate zones (CZs) (j), and per crop the number of selected CZs (k,m,o) and the area covered by those selected CZs (l,n,p).

Country	a Wheat area (1000 ha)	b Barley area (1000 ha)	c Maize area (1000 ha)	d Spring sown wheat (%)	e Autumn sown wheat (%)	f Spring sown barley (%)	g Autumn sown barley (%)	h Rainfed maize	i Irrigated maize	j All CZs (n)	k Selected CZs wheat (n)	l Area cover for wheat (%)	m Selected CZs barley (n)	n Area cover for barley (%)	o Selected CZs maize (n)	p Area cover for maize (%)
Albania	78	2	47		100		100		Y	13	6	70	6	69	6	74
Austria	289	197	177		100	55	45	Y		12	8	94	8	93	7	96
Belarus	357	617	29	20	80	100		Y		11	7	97	7	97	5	85
Belgium	211	43	55		100		100	Y		5	3	98	3	96	1	99
Bosnia	81	21	195		100		100	Y		13	5	37	5	37	4	26
Herzegovina																
Bulgaria	1,031	258	341		100		100	Y		23	5	97	4	96	4	93
Croatia	180	52	346		100		100	Y		17	6	95	6	93	5	93
Cyprus	6	52			100		100			10	3	67	3	93		
Czech Republic	822	507	93		100	71	29	Y		14	6	94	6	94	5	97
Denmark	662	679			100	100				3	2	99	2	99		
Estonia	85	138		63	37	100				4	2	97	2	97		
Finland	209	560		85	15	100				6	3	99	3	98		
France	5,244	1,631	1,645		100	29	71	Y	Y	26	10	95	8	95	11	97
Germany	3,128	1,981	435		100	30	70	Y		16	9	97	10	98	7	91
Greece	808	93	235		100		100	Y	Y	37	8	73	8	54	8	70
Hungary	1,120	312	1,197		100	40	60	Y		8	6	98	6	98	6	97
Ireland	94	170		30	70	84	16			5	3	98	3	97		
Italy	2,131	318	1,139		100		100	Y		33	9	84	8	83	6	84
Kosovo	83	1	42		100		100	Y		15	3	41	3	41	2	44
Latvia	190	142		33	67	100				7	2	85	2	87		
Lithuania	356	341		38	62	100				11	3	93	3	89		
Luxembourg	12	10	0		100		100			4	1	89	1	99		
Macedonia	102	47	33		100		100	Y		22	4	69	4	72	3	46
Moldova	336	118	492		100	44	56			7	4	99	4	99	4	100
Montenegro	1	1	3		100		100	Y		6	6	100	6	100	5	83
Netherlands	133	47	20		100	100		Y		2	2	100	2	100	1	100
Norway	83	147		85	15	100				5	1	88	1	87		
Poland	2,233	1,115	351		100	85	15	Y		17	9	95	9	96	8	97
Portugal	138	31	117		100		100		Y	36	8	89	6	89	13	69
Romania	2,239	406	2,774		100	38	62	Y		26	7	87	7	83	7	87
Serbia	531	92	1,155		100		100	Y		21	3	79	3	77	3	81
Slovakia	365	204	152		100	100		Y		14	9	96	9	97	6	98
Slovenia	31	16	43		100		100	Y		7	5	99	5	98	4	97
Spain	2,122	3,177	412		100		100	Y	Y	48	13	82	10	82	16	66
Sweden	367	357			100	100				11	5	98	6	97		
Switzerland	90	37	19		100		100	Y		10	5	99	5	99	4	95
Ukraine	5,790	4,659	1,881		100	100		Y		30	10	86	7	85	5	81
United Kingdom	1,881	933			100	60	40			13	6	98	7	98	7	

parameters for calibration were, in order of importance, SLATB (specific leaf area [ha kg^{-1}]), the partitioning of assimilates to the various organs (FSTB for stems, FLTB for leaves and FOTB for storage), SPAN (life span of leaves growing at 35°C [d]) and AMAX (maximum leaf CO_2 assimilation [$\text{kg ha}^{-1} \text{h}^{-1}$]). The final evaluation step consisted of an expert assessment by the country agronomist, and if available, supported by annual maximum yields observed in variety trials or agronomic experiments (Supplement 2). If the average simulated yields were more than 15% lower or higher than the observed maximum yields, or if the experts qualified the simulations not plausible, further fine-tuning of the crop parameters, as described above, was carried out.

The simulations were carried out for each STU within a RWS zone. The simulation results were up-scaled successively to SMU, RWS, CZ and country, using harvested area per STU as weighing factor. All simulated crop yields are presented at standard moisture content, i.e. 13.5% for wheat and barley, and 15.5% for maize.

2.5. Actual yields

The actual annual grain yields (Y_a) were obtained from national statistical offices at the best available spatial resolution (NUTS levels 1, 2 or 3 representing increasing regional resolution; <http://ec.europa.eu/eurostat/web/nuts/overview>) and at the most disaggregated crop and cropping system level (spring sown or autumn sown common or durum wheat, spring sown or autumn sown barley, rainfed maize, and irrigated maize). Yield data were collected for a recent period of 10 years for rainfed crops and 5 years for irrigated crops (Grassini et al., 2015b). A linear trend analysis was carried out to identify countries with a significant ($P < 0.05$) increasing trend. For those countries with increasing trends, only the recent 5 year period was used to avoid effects of technological developments. The actual yields were re-scaled from the NUTS region to the RWS zone, and subsequently to CZ and country, using the harvested area (You et al., 2014) as weighing factor. All actual crop yields are presented at standard moisture content, i.e. 13.5% for wheat and barley, and 15.5% for maize.

2.6. Yield gap

The yield gap of rainfed crops is calculated as the difference between the water-limited yield (Y_w) and actual yield (Y_a), whereas the yield gap of irrigated maize equals the difference between the potential yield (Y_p) and the actual yield (Y_a). The yield gaps are also expressed relative to Y_w ($[1 - Y_a/Y_w] * 100\%$) or Y_p ($[1 - Y_a/Y_p] * 100\%$).

2.7. Actual nitrogen use

Crop and country specific actual N inputs from fertilizer and manure were derived from the MITERRA model (Velthof et al., 2009; Velthof et al., 2014) for the year 2010, for the EU member states. In these approaches, fertilizer application is based on data of the European Fertilizer Manufacturer's Association published by FAOSTAT and expert questionnaire data from the International Fertilizer Association (IFA). Within the boundaries of the total fertilizer and manure use at country level, fertilizer and manure N were allocated to crops, mainly based on actual above ground crop N uptake. Total manure N was converted to fertilizer equivalents, assuming a default N fertilizer replacement value of all manure types and for all crops of 50%, based on the ranges found throughout Europe (Webb et al., 2013).

2.8. Nitrogen gap

We define the N uptake gap as the difference between the above ground N uptake at 80% of Y_w (Van Ittersum et al., 2013) and the N uptake at Y_a . The N uptake gaps were calculated from the yield gaps using the procedure of De Vries et al. (2018) developed within the Crop Nutrient Gap Project (<http://www.yieldgap.org>). The approach is based

on an inversed, target-oriented, approach of the QUEFTS model (Janssen et al., 1990), using the following minimal and maximal values for the physiological N efficiency in above ground biomass: for maize 30 and 70, for wheat 20 and 46, and for barley 21 and 49 kg grain yield (at standard moisture content) per kg N uptake. These values are consistent with the average nutrient removal values of the IPNI Crop Nutrient Removal Calculator (<http://www.ipni.net/article/IPNI-3346>), and with ranges observed in literature (Le Gouis et al., 1999; Ciampitti and Vyn, 2012; Sattari et al., 2014; Ruisi et al., 2015; Baral et al., 2017; Rajala et al., 2017). The N uptake gap may be considered a minimal additional N requirement needed to increase the actual yield to 80% of the yield potential. The actual additional N requirement depends on the efficiency with which applied N is taken up by the crop.

3. Results

3.1. Actual yields

Actual yields of rainfed wheat varied from 1.2 to 8.9 t ha^{-1} (Fig. 1a). Relatively low yields were observed in Mediterranean and Eastern Europe. Areas with yields below the 10th percentile (2.5 t ha^{-1}) were Cyprus, Moldova and Portugal, as well as some climate zones in Greece, Italy, Spain and Ukraine. Relatively high yields were observed in north-western Europe. The highest yields (90th percentile; $> 7.4 \text{ t ha}^{-1}$) were observed in Belgium, Ireland and Netherlands, all but one climate zone in United Kingdom, and some climate zones in France, Germany and Sweden. Autumn sown wheat is the dominant cropping system in most countries throughout Europe. Spring sown wheat is mainly grown in the northern countries with average yields up to 30% lower than those of autumn sown wheat.

The actual yields of rainfed barley varied from 1.5 to 8.1 t ha^{-1} (Fig. 1d) and showed a similar regional distribution as that of rainfed wheat. Relatively low yields were observed in Mediterranean and Eastern Europe. In addition to the regions mentioned for wheat, areas with yields below the 10th percentile (2.2 t ha^{-1}) were also found in some climate zones in Latvia and Romania. Relatively high yields were observed in north-western Europe. The highest yields (90th percentile; $> 6.3 \text{ t ha}^{-1}$) were mainly observed in the same countries as for wheat, but also in Switzerland. Relative to wheat, barley yielded approximately 70 to 110%. In the Mediterranean countries, barley generally had higher yields than wheat, because of the presence of durum wheat in these regions, which generally yields less than common wheat and because barley is harvested earlier and is thus less affected by summer drought. The proportion of spring sown barley varied from 0%, mainly in the Mediterranean, to 100%, mainly in the Nordic regions. Spring barley yields were between 5 and 25% lower than the yields of autumn sown barley. Spring barley has a shorter growing season than winter barley, but it also receives less fertilizer N as it is predominantly grown as malting barley.

The actual yields of rainfed maize (Fig. 2a) varied from 2.9 to 11.8 t ha^{-1} , and showed a similar regional distribution as that of wheat and barley, bearing in mind that grain maize is not grown everywhere throughout Europe. Areas with yields below the 10th percentile (3.5 t ha^{-1}) were Kosovo and Moldova, as well as most climate zones in Romania. Relatively high yields were observed in north-western Europe. The highest yields (90th percentile; $> 10.0 \text{ t ha}^{-1}$) were observed in Belgium and Netherlands, as well as a climate zone in Austria.

Irrigated maize yields (Fig. 2d) showed a relatively small variation, around 10 t ha^{-1} , throughout Spain, France, Italy and Greece. Yields in Albania and northern Portugal were considerably lower at levels around 6 t ha^{-1} .

The coefficient of variation ($\text{CV} = \text{standard deviation}/\text{mean}$) of the actual yields, reflecting inter-annual variation, of rainfed wheat varied from 5 to 10% in northern and western Europe to 10 to 20% in southern and eastern Europe, with some individual countries (Moldova and Romania) above 25%. Actual barley yields generally showed a lower CV

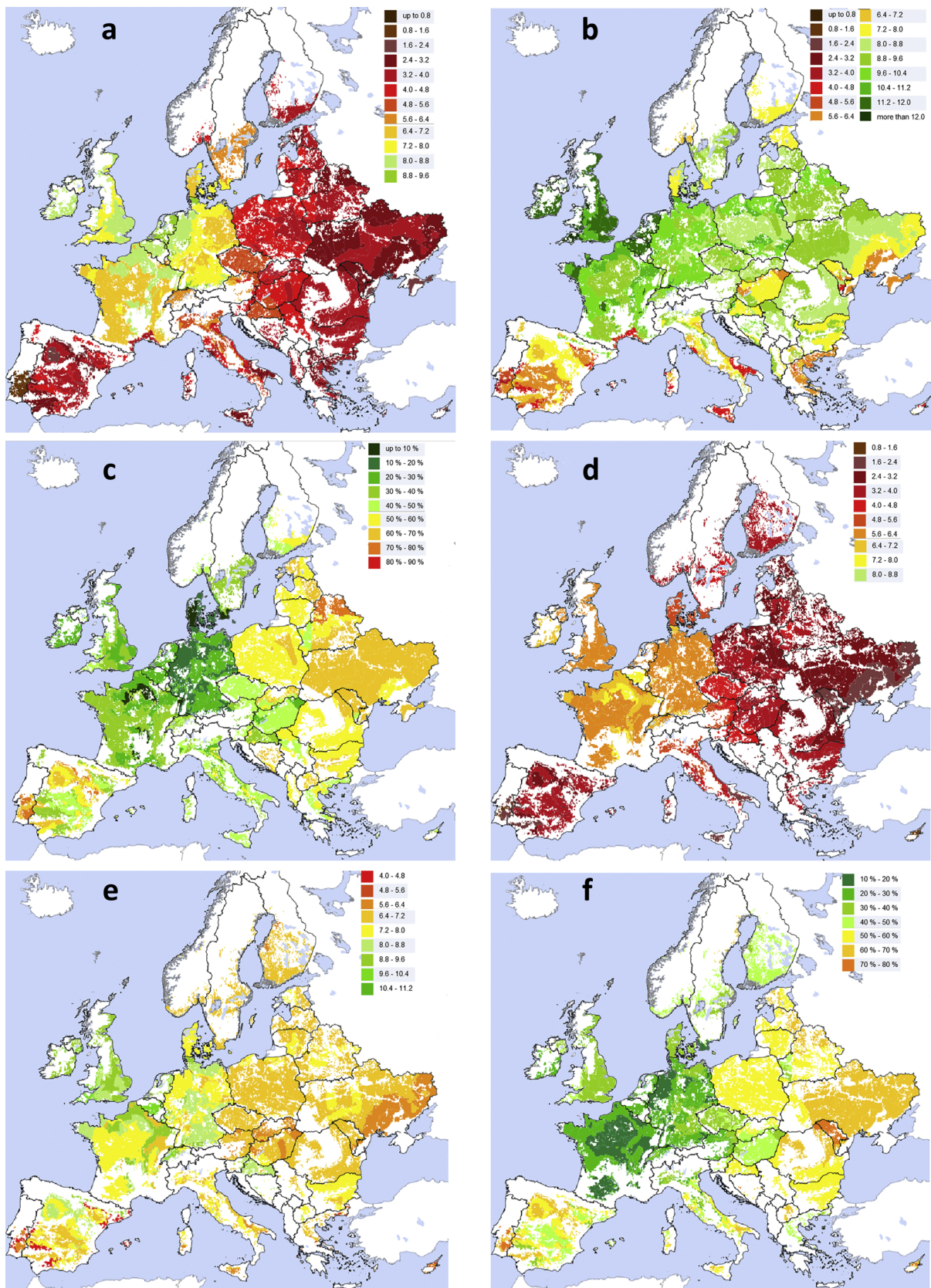


Fig. 1. Average crop yields ($t\ ha^{-1}$ at standard moisture content) and yield gaps (% of yield potential) of rainfed wheat (a,b,c) and rainfed barley (d,e,f) for climate zones in countries; actual yield (a,d), water-limited yield (b,e) and yield gap (c,f). Crop area mask of You et al. (2014).

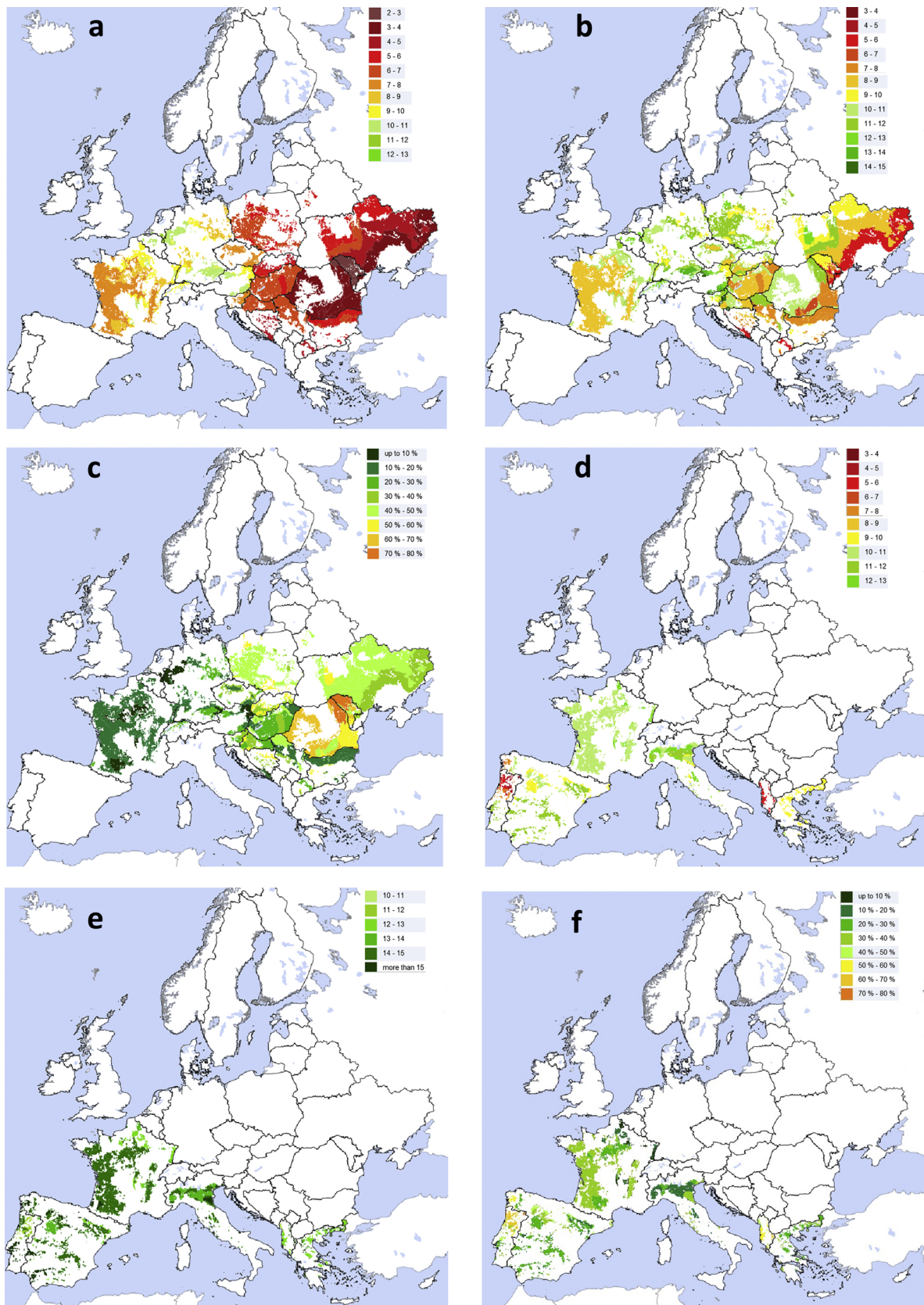


Fig. 2. Average crop yields (t ha⁻¹ at standard moisture content) and yield gaps (% of yield potential) of rainfed maize (a,b,c) and irrigated maize (d,e,f) for climate zones in countries. Actual yield (a,d), water-limited yield (b), potential yield (e) and yield gap (c,f). Crop area mask of You et al. (2014).

with a predominantly west-east increasing gradient. The CV of actual rainfed barley yields in Portugal was exceptionally high (34%). The actual rainfed maize yields generally showed a higher CV, again with a predominantly west-east increasing gradient, from around 10% to 25%. Some countries (Bulgaria, Moldova and Romania) had a CV above 25%. The CV of actual yields in irrigated maize was mostly less than 15%, with the exception of Greece (22%). In these environments, heat stress around flowering may increase variability, despite irrigation.

3.2. Water-limited and potential yields

The simulated water-limited yields of wheat varied from 3.8 to 12.9 t ha⁻¹ (Fig. 1b). There was a clear west-east and central-south gradient that relates to the length of the growing season and the precipitation deficit. In Norway and Finland the yield was relatively low, primarily due to the high proportion of spring wheat, whereas the yield in Sweden was relatively high among Nordic countries as the selected areas only comprised winter wheat.

The simulated water-limited yields of barley (Fig. 1e) varied from 4.4 to 10.6 t ha⁻¹, and showed a similar, but less extreme, regional distribution as that of wheat. Relative to wheat, barley yielded approximately 70 to 115%, similar to the findings for actual yields.

The simulated water-limited yields of maize varied from 3.2 to 14.9 t ha⁻¹ (Fig. 2b), showing also a west-east and central-south gradient. Potential yields of irrigated maize (Fig. 2d) showed a relatively small variation between 10.6 to 17.5 t ha⁻¹, with a slightly increasing gradient from north to south.

3.3. Yield gap

The yield gaps of rainfed wheat varied from 0.2 to 6.9 t ha⁻¹, which equals relative gaps from 2 to 84% (Fig. 1c). Relative yield gaps lower than 10% occurred in 4 out of the 204 CZs (2%), possibly related to an underestimation of Yw in those CZs. Relative yield gaps below 30% were observed in many north-western countries, while relative yield gaps above 50% were mainly found in eastern and south-western Europe. For rainfed barley (Fig. 1f) the overall picture was quite similar to that of wheat, with absolute gaps between 1.0 and 7.3 t ha⁻¹ and relative yield gaps between 12 and 75%.

The yield gaps of rainfed maize varied from 0 to 8.9 t ha⁻¹, or from 0 to 75% (Fig. 2c). Relative yield gaps lower than 10% occurred in 7 out of the 103 CZs (7%), possibly indicating an underestimation of Yw. Relative yield gaps below 30% were observed in Western Europe, while relative yield gaps above 40% were mainly seen in Eastern Europe. For irrigated maize (Fig. 2f), the absolute gaps varied between 0.5 and 12.5 t ha⁻¹ and relative gaps between 4 and 78%.

The national relative yield gaps were inversely related to Gross Domestic Product (GDP) per capita, for GDPs lower than ca. USD 40,000 (Fig. 3), with an average slope of 0.8% per 1000 USD. Above a GDP of ca. USD 40,000 yield gaps were not related to income. The relationship between yield gap and GDP was similar for all crops, but the yield gaps for rainfed and irrigated maize were approximately 10–20%-points lower than those of rainfed wheat and barley.

3.4. Cereal production

The current combined production of wheat, barley and maize in Europe amounts to 327 Mt. France is the largest producer (Fig. 4), responsible for 19% of the production, followed by Germany (12%) and Ukraine (11%). Overall, 93% of the total production is produced by 50% of the countries. The consolidated yield gap is 239 Mt, or 42% of the yield potential. If the yield gap would be reduced to 20% of Yw or Yp, this would increase production by 128 Mt, of which 54% is the combined share of Ukraine, Romania and Poland.

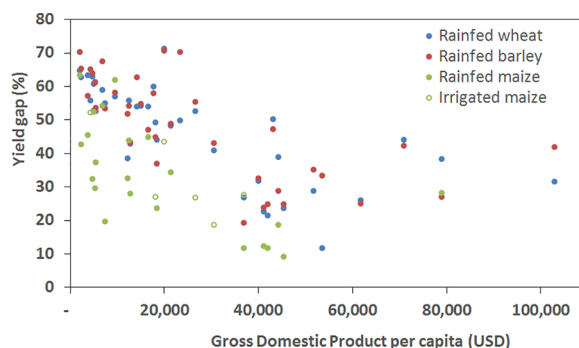


Fig. 3. Relative yield gap (%) for all crops, in relation to national GDP (USD/capita; <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD>).

3.5. Nitrogen

3.5.1. Actual nitrogen use

In 2010, the actual total N input, expressed in fertilizer N equivalents, from fertilizer and manure for the three cereals in the EU-28 was 4.2 Mt, of which 60%, 18% and 22% was allocated to wheat, barley and maize, respectively. The average N application per ha increased in the order barley < wheat < maize, but showed a large variation between countries (Fig. 5), i.e. from 24 to 297 kg N ha⁻¹. The average amount of N applied per 1000 kg of wheat, barley or maize was 23, 16 or 17 kg, respectively. Countries with a relatively low N application per 1000 kg grain (< 10th percentile) were Sweden, Italy, Romania and Austria, while the countries with the largest application per 1000 kg grain (> 90th percentile) were Finland, Portugal, Greece, Croatia and Cyprus. The latter are the points located below the 1-to-1 line in Fig. 5 (right), indicating that the N application exceeds the N uptake. The majority of points are located above this line, as the crops also benefit from other N sources than fertilizer and manure, such as atmospheric deposition, legumes in the rotation and mineralisation of organic matter in manure and other added organic matter.

3.5.2. Nitrogen uptake gap

The N uptake gap varied between 0 and approximately 150 kg N ha⁻¹ for wheat and barley, and between 0 and approximately 100 kg N ha⁻¹ for maize (Fig. 6), with average values for wheat, barley and maize of 87, 77 and 43 kg N ha⁻¹, respectively. Countries with low yield gaps had low additional N requirements, and vice versa. The N uptake gap represents the minimum input requirement to reduce the yield gap to 20%.

The total N uptake gap for the countries included in this analysis amounted to 4.8 Mt of N, of which 57%, 30% and 13% is required for wheat, barley and maize, respectively. The N uptake gap for the EU28 countries amounted to 3.0 Mt. Similar to the cereal production gap, the largest share of the N uptake gap was located in Eastern Europe, with Ukraine, Romania and Poland together accounting for 49% of the total N uptake gap.

4. Discussion

4.1. Uncertainty

The GYGA protocol applies a tiered data approach, i.e. it uses the highest data quality available, but also allows the use of lower quality data when necessary (Grassini et al., 2015a). This implied a varying data quality and associated uncertainty across the countries included in our analysis. Yet, we argue that this is the agronomically most robust yield gap assessment for Europe to date.

Van Bussel et al. (2015) found that estimated national water-limited yield potentials were robust if data could be collected that were representative for approximately 50% of the national harvested area of a

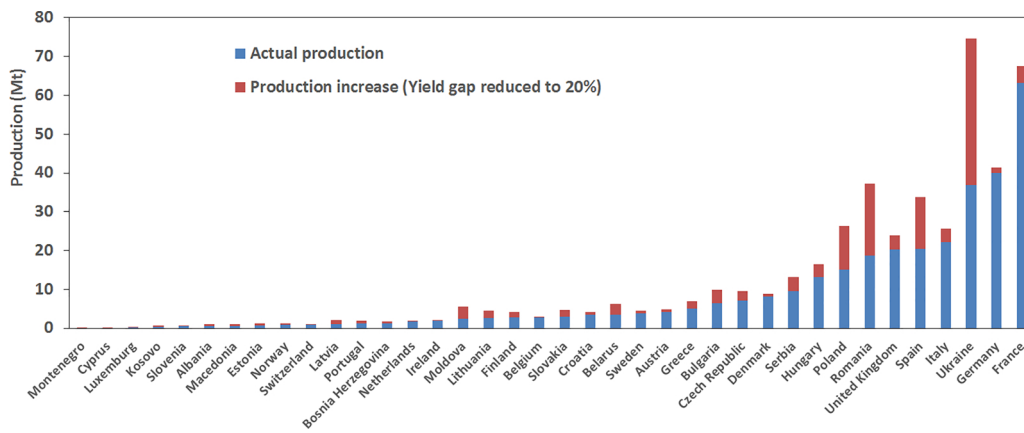


Fig. 4. Actual consolidated production (Mt; standard moisture content) of wheat, barley and maize, and additional production when the yield gaps are reduced to 20% of Yw or Yp.

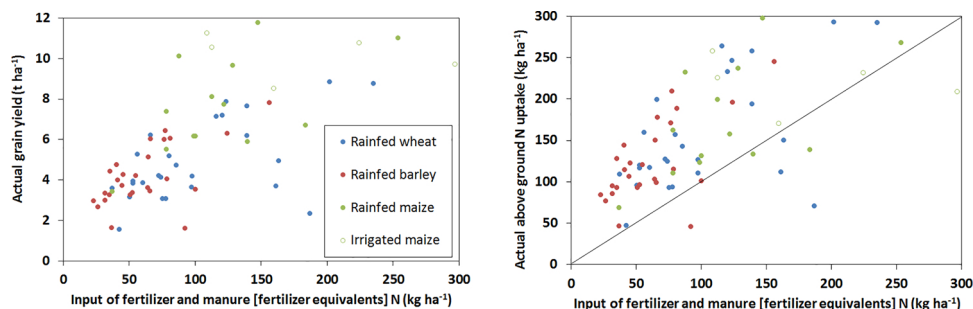


Fig. 5. Actual grain yield (left) and above ground N uptake (right) of wheat, barley and maize in relation to the actual nitrogen input of fertilizer and manure, expressed as fertilizer equivalents, for EU countries.

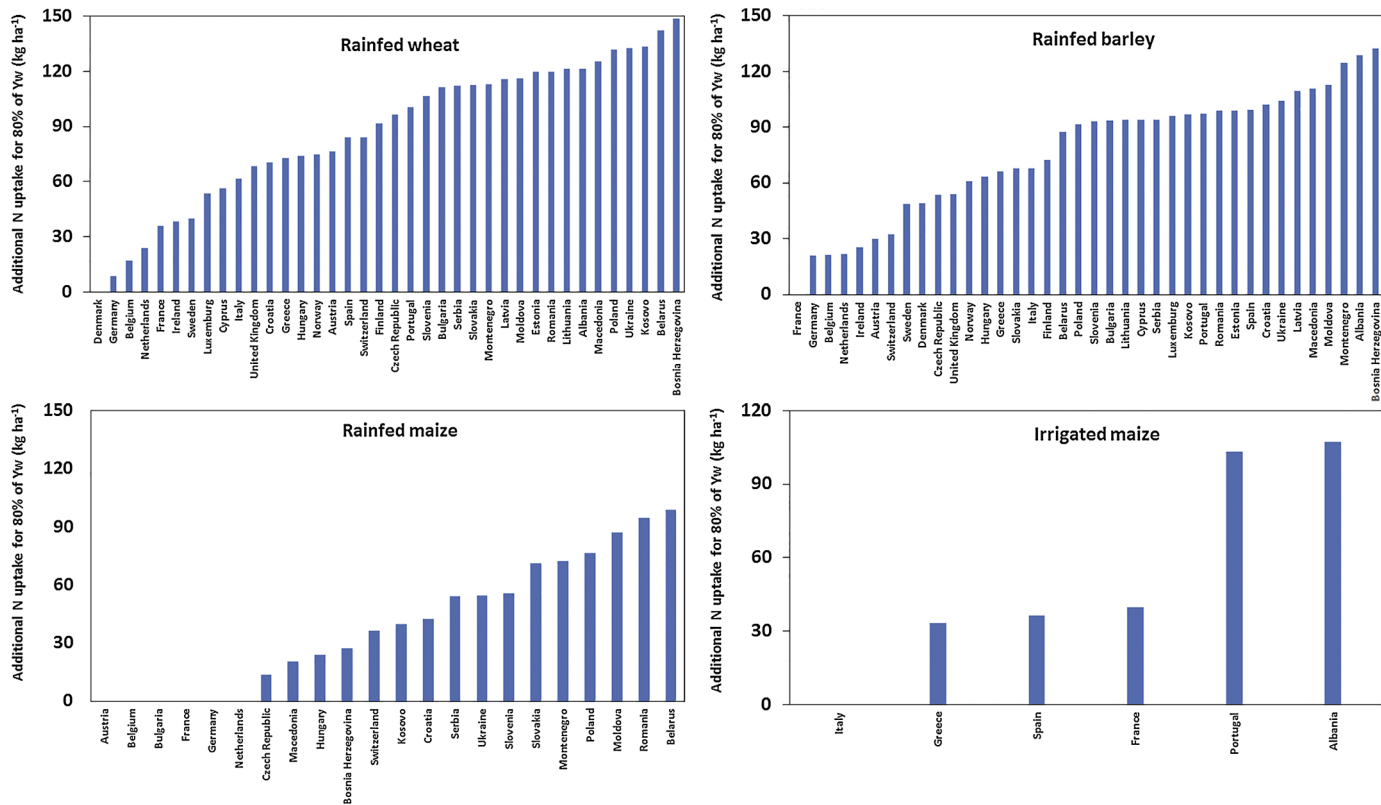


Fig. 6. Additional nitrogen uptake when yields increase from the actual yield to 80% of the water-limited yield (rainfed wheat, barley and maize) or to 80% of the potential yield (irrigated maize).

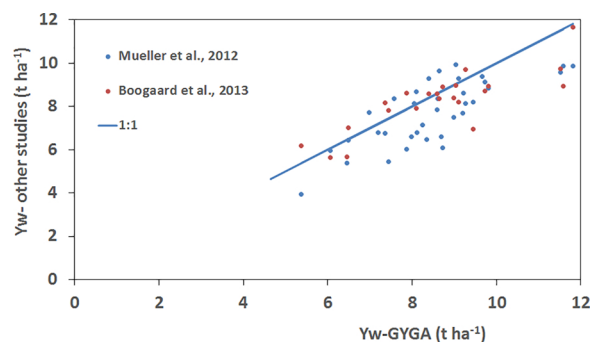


Fig. 7. Comparison of water-limited yield potential in Boogaard et al. (2013) and attainable yield in Mueller et al. (2012) with water-limited yield potential in the present study for rainfed wheat at standard moisture content.

crop. For wheat grown in Australia, Hochman et al. (2016) showed a high level of agreement between the GYGA approach, with 50% area cover, and a so-called ‘data rich’ approach with 94% area cover. In Europe, the availability of actual weather data at sufficient temporal and spatial scales resulted in a high coverage, 88% on average, of the harvested area in the selected CZs. Relatively low coverages were observed in some countries in central and southern Europe, with large topographical variations at short distances, resulting in many small CZs. In some countries of the Former Republic of Yugoslavia (Bosnia Herzegovina, Kosovo, Macedonia and Montenegro) as well as Albania and Moldova, the availability of weather records was too low, which resulted in the use of gridded weather data.

The calculation of the growing degree days in the GYGA climate zonation scheme is based on a base temperature of 0 °C for all crops (Van Wart et al., 2013). The main arguments for this approach are that much of the world's cropland produces more than one major food crop and that it facilitates analysis of yield gaps for crop rotations. Nevertheless, we realize that a crop-specific zonation for maize, with a base temperature of 8 °C, would result in a slightly different climate zonation compared to that of wheat and barley.

For most of the countries in this study, actual yields were available at a sufficient temporal and spatial detail, and also disaggregated to the relevant cropping system, i.e. spring sown vs. autumn sown, rainfed vs. irrigated or common vs. durum wheat. For Kosovo, actual yields were only available for a single year.

We used the SPAM2005 crop mask (You et al., 2014) for identifying areas of cereal cultivation. This is the most recent SPAM version currently available, while an update to 2010 is anticipated in the near future. In the EU, crop areas of wheat, barley and maize did change between 2005 and 2013, on average with a factor 1.03, 0.88 and 1.06, respectively (Eurostat, 2018). The average yield gap per country is only affected if area changes are not uniform across the various climate zones and soil types within a country. The unlocked production potential per country, however, is also affected by uniform area changes. Until an updated crop mask is available our estimations cannot be improved.

In the definitions of the Global Yield Gap Atlas, rainfed crops are not irrigated at all, while irrigated crops are irrigated to compensate for all potential water stress, so yield potential can be achieved. In practice, the distinction is less strict, and some caution is needed in interpretation. In drought prone areas throughout Europe, temporal water stress may be reduced by supplemental or partial irrigation. This is most prominent in Mediterranean countries where permanently installed irrigation equipment for maize may also be used for strategic irrigation of wheat and barley, but even in northern Europe, cereals on sandy soils may be partially irrigated (Olesen et al., 2000; Gobin et al., 2017). Therefore, any underestimated contribution of irrigation in assumed rainfed crops may have led to an underestimated yield potential and to underestimation of yield gaps.

Much effort was put into collecting and verifying phenological data for all cropping systems per country-CZ combination, needed for a regional calibration of the crop varieties representative for those zones. For some countries the calibration was further strengthened through observed grain yields in field experiments. Even when we had no access to experimental data, the arrangement with a country agronomist ensured an assessment of the plausibility of the simulated yields, given their knowledge of locally realised yields on experimental sites.

This study did not take into account the effects of climate change. A review (Olesen and Bindi, 2002) of cereal studies indicated a larger yield increase or a smaller yield reduction in northern Europe compared to southern Europe. For wheat, Olesen and Bindi (2002) calculated that the yield increases due to technological improvements were three times larger than yield increases due to climate change. However, there was a large regional variation with a relatively large impact of climate change in the Mediterranean and Western Europe and a relatively large impact of technology in Eastern Europe. Increasingly variable weather conditions (Trnka et al., 2011) and occurrence of meteorological extremes (Trnka et al., 2015) will increase the risk of investment in additional nutrient inputs, and thus hamper yield benefits of increasing input levels in those areas (Swinnen et al., 2017). Increasing summer drought might decrease N efficiency for some sites (Kersebaum and Nendel, 2014). Thus, whether the potential of reducing yield gaps will be realized, will certainly depend on climate change.

4.2. Comparison to other studies

Boogaard et al. (2013) simulated rainfed autumn sown wheat yields for EU-25 countries, using the WOFOST crop model with gridded weather data. The average national water-limited yields (Yw) of the GYGA approach were 4% higher than in the approach of Boogaard et al. (2013), ranging from -13% (Portugal) to +36% (Poland) (Fig. 7). The likely underestimation of the simulated yield for Poland, possibly through an overestimation of drought stress, is specifically mentioned in Boogaard et al. (2013). Mueller et al. (2012) estimated attainable yields as the 95th percentile of actual yields in a similar climate bin (100 zones of similar annual precipitation and growing degree days), using empirically derived input-yield crop models. The differences between our analysis and the global study of Mueller et al. (2012) were larger, with an average of +12% for GYGA, and a range of -10% (Austria) to +44% (Sweden). For both studies, deviations from our results did not seem to be systematically associated to specific regions in Europe.

4.3. Yield gaps, production potentials and the environment

The potential to enhance cereal production in Europe through reducing the yield gap is largest in Eastern Europe. Reducing the yield gaps to 20% of Yw or Yp, would increase the consolidated production of wheat, barley and maize from 327 to 456 Mt. Approximately half of the production increase could occur in Ukraine, Romania and Poland. Our study only considered reducing yield gaps on existing cropland, whereas re-cultivation of abandoned farmland, which is widespread in temperate European Russia, northern and western Ukraine, and Belarus (Alcantara et al., 2013), can also contribute to increased production. For Ukraine, Swinnen et al. (2017) estimated a production growth of 26.7 Mt due to intensification to 80% of the yield potential, and a relatively modest production growth of 1.7 Mt due to re-cultivation. Similar conclusions were drawn by Deppermann et al. (2018), who found that production potentials, in Russia and Ukraine, due to intensification were ten times larger than potentials due to re-cultivation of abandoned land. In our approach we assumed a default value of 80% of Yw (rainfed) or Yp (irrigated) as a maximum production target, but a further elaboration of regionally sustainable production targets is necessary, depending on the specific climate, soil and management.

Low yield gaps were mainly observed in north-western Europe,

leaving a relatively smaller scope for further yield improvement in comparison to Eastern Europe. Sylvester-Bradley (2010) distinguished four technologies whereby yields may be enhanced in future, i.e. breeding, engineering, chemistry and farming logistics. The latter three options are most likely to be the main basis for yield gap reduction in Eastern Europe, while breeding provides further prospect for yield increases in Western Europe. Fischer et al. (2014) presented a global summary of progress in potential yields, arriving at an average annual progress of 0.61% in wheat. The recent stagnation in actual wheat yields observed in several countries in north-western Europe, was suggested to indicate that the genetic progress is offset by climate change, a lower proportion of legumes in rotations and reduced N application (Brisson et al., 2010), although differences exist across countries (Rijk et al., 2013).

Yield gaps were inversely related to per capita GDP, as was also observed earlier for a wider analysis that included countries in Africa, Asia, Australia and the Americas (Van Ittersum et al., 2016a). High income countries are better able to invest in knowledge, equipment, fertilizers and crop protection to increase crop yields. At the same time, in many cases, a productive agricultural sector is a pre-requisite for increased productivity in the secondary and tertiary sectors (Gollin, 2010).

Unlocking the identified potential for production growth requires a substantial increase of the N uptake, to be achieved by higher N use efficiencies, but regionally also by higher N inputs. Incentives to reduce yield gaps may thus bring considerable challenges for reducing the associated negative environmental impacts of enhanced N use. These impacts include nitrate leaching, which threatens quality of groundwater for human consumption and contributes to eutrophication of both freshwater and marine ecosystems. This challenges current policy objectives such as those of the EU Nitrates Directive, the EU Water Framework Directive and the Baltic Sea Action Plan. Higher N inputs would also enhance risk of ammonia volatilisation leading to higher N deposition and formation of aerosols. Higher use of N fertilizers enhances nitrous oxide emissions, which conflicts with policy targets to reduce greenhouse gas emissions. Emphasis on tightening N cycling in agriculture thus needs to go along with closing the yield gap, which aligns with the aim of the EU Nitrogen Expert Panel (<http://www.eunep.com/>) to contribute to improving Nutrient Use Efficiency (NUE) in food systems in Europe.

It has been argued that the increased input of nutrients in eastern Europe (Van Grinsven et al., 2014) or other underperforming regions across the globe (Nathaniel et al., 2014) can be partly compensated by reduced inputs in currently intensively managed regions. Mueller et al. (2012) suggested a reduction of N input in large parts of Western Europe. The sensitivity of the additional N requirements to N use efficiency underscores the importance of optimal N management. It needs to be considered that N use efficiency cannot be seen isolated from other management factors such as crop protection, and supply of water and other nutrients (De Wit, 1992). Alleviating these yield limiting or reducing factors may enhance N uptake without further increasing N inputs. This is equally true for underperforming regions, where the challenge lies in increasing yields with modestly increased N inputs, and for current high yielding regions and particularly nitrate vulnerable zones where the challenge lies in maintaining yields with reduced N inputs. A recent study by Lassaletta et al. (2014) suggests that a further increase of N fertilization would result in a disproportionately low increase of crop production with additional negative environmental effects, unless cropping systems improve their efficiency substantially.

5. Conclusions

Yield gaps were estimated for rainfed wheat and barley, and rainfed and irrigated grain maize using an agronomically robust and consistent country-by-country approach. The yield gaps showed a wide range from 10 to 70% of potential yields, with small gaps in many north-western

European countries, and large gaps in eastern and south-western Europe. Yield gaps for rainfed and irrigated maize were consistently lower than those of wheat and barley.

The consolidated yield gap of wheat, barley and maize was 239 Mt, or 42% of the yield potential. If the yield gap would be reduced to 20% of the yield potential, the production would increase by 128 Mt (39%). The potential for increased cereal production exists mainly in Eastern Europe, with approximately half of it in Ukraine, Romania and Poland.

Unlocking the identified potential for production growth in Europe requires a substantial increase of the crop N uptake of 4.8 Mt. The average N uptake gaps were 87, 77 and 43 kg N ha⁻¹ for wheat, barley and maize, respectively. The required additional N input to realize the increased crop production and N uptake can be minimized through emphasis on increasing the N use efficiency and good agronomy.

Acknowledgements

We received financial contributions from the strategic investment funds (IPOP) of Wageningen University & Research, Bill & Melinda Gates Foundation, MACSUR under EU FACCE-JPI which was funded through several national contributions, and TempAg (<http://tempag.net/>).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.eja.2018.09.003>.

References

- Alcantara, C., Kuemmerle, T., Baumann, M., Bragina, E.V., Griffiths, P., Hostert, P., Knorn, J., Müller, D., Prishchepov, A.V., Schierhorn, F., 2013. Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data. *Environ. Res. Lett.* 8, 035035.
- Alexandratos, N., Bruinsma, J., 2012. World Agriculture towards 2030/2050: the 2012 Revision. ESA Working Paper Rome. FAO.
- Baral, K.R., Labouriau, R., Olesen, J.E., Petersen, S.O., 2017. Nitrous oxide emissions and nitrogen use efficiency of manure and digestates applied to spring barley. *Agric. Ecosyst. Environ. Appl. Soil Ecol.* 239, 188–198.
- Boogaard, H., Van Diepen, C., Rotter, R., Cabrera, J., Van Laar, H., 1998. WOFOST 7.1; User's Guide for the WOFOST 7.1 Crop Growth Simulation Model and WOFOST Control Center 1.5. SC-DLO.
- Boogaard, H., Wolf, J., Supit, I., Niemeyer, S., Van Ittersum, M., 2013. A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union. *Field Crops Res.* 143, 130–142.
- Boons-Prins, E., De Koning, G., Van Diepen, C., 1993. Crop-specific Simulation Parameters for Yield Forecasting across the European Community. CABO-DLO.
- Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.-X., Huard, F., 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Res.* 119, 201–212.
- Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proc. Natl. Acad. Sci.* 96, 5952–5959.
- Ceglar, A., van der Wijngaart, R., de Wit, A., Lecerf, R., Boogaard, H., Seguin, L., van den Berg, M., Toreti, A., Zampieri, M., Fumagalli, D., Baruth, B., 2018. Improving WOFOST model to simulate winter wheat phenology in Europe: evaluation and effects on yield. *J. Agric. Food Syst. Commun. Dev.* <https://doi.org/10.1016/j.agry.2018.05.002>.
- Ciampitti, I.A., Vyn, T.J., 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: a review. *Field Crops Res.* 133, 48–67.
- De Vries, W., Kros, J., Kroeze, C., Seitzinger, S.P., 2013. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Curr. Opin. Environ. Sustain.* 5, 392–402.
- De Vries, S.C., Ten Berge, H.T.M., Van Ittersum, M.K., 2018. Estimating Nutrient Uptake & Inputs Gaps. <http://www.yieldgap.org/web/guest/minimum-nitrogen-input-requirement> [accessed September 10, 2018].
- De Wit, C.T., 1992. Resource use efficiency in agriculture. *J. Agric. Food Syst. Commun. Dev.* 40, 125–151.
- De Wit, A., Boogaard, H., Fumagalli, D., Janssen, S., Knapen, R., Van Kraalingen, D., Supit, I., Van Der Wijngaart, R., Van Diepen, K., 2018. 25 Years of the WOFOST Cropping Systems Model. *Agric. Syst.* <https://doi.org/10.1016/j.agry.2018.06.018>.
- Deppermann, A., Balkovič, J., Bundle, S.-C., Fulvio Di, F., Havlik, P., Leclère, D., Lesiv, M., Prishchepov, A.V., Schepaschenko, D., 2018. Increasing crop production in Russia and Ukraine—regional and global impacts from intensification and recultivation. *Environ. Res. Lett.* 13, 025008.
- Dobermann, A., Cassman, K.G., 2005. Cereal area and nitrogen use efficiency are drivers

- of future nitrogen fertilizer consumption. *Sci. China Ser. B Chem. Life Sci. Earth Sci.* 48, 745–758.
- EU, 2014. EU CEREAL FARMS REPORT 2013. European Union, Brussels, pp. 122.
- EU, 2016. EU Cereals Balance Sheet 2016/17 and Forecast 2017/18. European Union, pp. 17.
- FAO, 2016. FAO Food Outlook. FAO, pp. 139.
- Fischer, R., Byerlee, D., Edmeades, G., 2014. Crop yields and global food security. *Crop Yields and Global Food Security: Will Yield Increase Continue to Feed the World?* ACIAR Monograph No. 158. Australian Centre for International Agricultural Research, Canberra, pp. 634.
- Gabrielle, B., Bamiere, L., Caldes, N., De Cara, S., Decocq, G., Ferchaud, F., Loyce, C., Pelzer, E., Perez, Y., Wohlfahrt, J., Richard, G., 2014. Paving the way for sustainable bioenergy in Europe: technological options and research avenues for large-scale biomass feedstock supply. *Renew. Sustain. Energy Rev.* 33, 11–25.
- Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable intensification in agriculture: premises and policies. *Science* 341, 33–34.
- Gobin, A., Kersebaum, K., Eitzinger, J., Trnka, M., Hlavinka, P., Takáč, J., Kroes, J., Ventrella, D., Marta, A., Deelstra, J., Lalić, B., Nejedlik, P., Orlandini, S., Peltonen-Sainio, P., Rajala, A., Saue, T., Şaylan, L., Stričević, R., Vučetić, V., Zoumides, C., 2017. Variability in the water footprint of arable crop production across European regions. *Water* 9, 93.
- Godfray, H.C.J., Garnett, T., 2014. Food security and sustainable intensification. *Philos. Trans. Biol. Sci.* 369, 20120273.
- Gollin, D., 2010. Agricultural Productivity and Economic Growth. *Handbook of Agricultural Economics*. Elsevier, pp. 3825–3866.
- Grassini, P., Van Bussel, L.G., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., De Groot, H., Van Ittersum, M.K., Cassman, K.G., 2015a. How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. *Field Crops Res.* 177, 49–63.
- Grassini, P., Van Bussel, L.G.J., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., De Groot, H., Van Ittersum, M.K., Cassman, K.G., 2015b. How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. *Field Crops Res.* 177, 49–63.
- Hochman, Z., Gobbett, D., Horan, H., Navarro Garcia, J., 2016. Data rich yield gap analysis of wheat in Australia. *Field Crops Res.* 197, 97–106.
- Janssen, B.H., Guiking, F.C.T., Van Der Eijk, D., Smaling, E.M.A., Wolf, J., Van Reuler, H., 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma* 46, 299–318.
- Kersebaum, K.C., Nendel, C., 2014. Site-specific impacts of climate change on wheat production across regions of Germany using different CO₂ response functions. *Eur. J. Agron.* 52, 22–32.
- Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci.* 108, 3465–3472.
- Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environ. Res. Lett.* 9, 105011.
- Le Gouis, J., Delebarre, O., Beghin, D., Heumez, E., Pluchard, P., 1999. Nitrogen uptake and utilisation efficiency of two-row and six-row winter barley cultivars grown at two N levels. *Eur. J. Agron.* 10, 73–79.
- Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. *Nature* 490, 254–257.
- Nathaniel, D.M., Paul, C.W., James, S.G., Graham, K.M., Stephen, P., Jonathan, A.F., 2014. A tradeoff frontier for global nitrogen use and cereal production. *Environ. Res. Lett.* 9, 054002.
- Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. *Eur. J. Agron.* 16, 239–262.
- Olesen, J.E., Mortensen, J.V., Jørgensen, L.N., Andersen, M.N., 2000. Irrigation strategy, nitrogen application and fungicide control in winter wheat on a sandy soil. I. Yield, yield components and nitrogen uptake. *J. Agric. Sci.* 134, 1–11.
- Panagos, P., Van Liedekerke, M., Jones, A., Montanarella, L., 2012. European Soil Data Centre: response to European policy support and public data requirements. *Land Use Policy* 29, 329–338.
- Rajala, A., Peltonen-Sainio, P., Jalli, M., Jauhiainen, L., Hannukkala, A., Tenhola-Roininen, T., Ramsay, L., Manninen, O., 2017. One century of Nordic barley breeding: nitrogen use efficiency, agronomic traits and genetic diversity. *J. Agric. Sci.* 155, 582–598.
- Rijk, B., Van Ittersum, M., Withagen, J., 2013. Genetic progress in Dutch crop yields. *Field Crops Res.* 149, 262–268.
- Rötter, R., Appiah, M., Fichtner, E., Kersebaum, K., Trnka, M., Hoffmann, M., 2018. Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes—a review. *Field Crops Res.* 221, 142–156.
- Ruisi, P., Frangipane, B., Amato, G., Frenda, A.S., Plaia, A., Giambalvo, D., Saia, S., 2015. Nitrogen uptake and nitrogen fertilizer recovery in old and modern wheat genotypes grown in the presence or absence of interspecific competition. *Front. Plant Sci.* 6.
- Sattari, S.Z., van Ittersum, M.K., Bouwman, A.F., Smit, A.L., Janssen, B.H., 2014. Crop yield response to soil fertility and N, P, K inputs in different environments: testing and improving the QUEFTS model. *Field Crops Res.* 157, 35–46.
- Supit, I., Hooijer, A., Van Diepen, C., 1994. System Description of the WOFOST 6.0 Crop Growth Simulation Model. Joint Research Center, Commission of the European Communities, Brussels, Luxembourg.
- Sutton, M., Howard, C., Erismann, J., Billen, G., Bleeker, A., Grennfelt, P., Van Grinsven, H., Grizzetti, B., 2011. The European Nitrogen Assessment. Cambridge Univ. Pres, Cambridge, UK.
- Swinnen, J., Burkitbayeva, S., Schierhorn, F., Prishchepov, A.V., Müller, D., 2017. Production potential in the “bread baskets” of Eastern Europe and Central Asia. *Glob. Food Secur.* 14, 38–53.
- Sylvester-Bradley, R., 2010. Targets, traits and technologies to achieve sustainable productivity with arable crops in the UK. *Asp. Appl. Biol.* 105, 107–114.
- Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci.* 108, 20260–20264.
- Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvag, A.O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Rötter, R., Iglesias, A., Orlandini, S., Dubrovski, M., Hlavinka, P.J.B., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vucetic, V., Nejedlik, P., Kumar, S., Lalic, B., Mestre, A., Rossi, F., Kozyra, J., Alexandrov, V., Semeradova, D., Zalud, Z., 2011. Agroclimatic conditions in Europe under climate change. *Glob. Change Biol. Bioenergy* 17, 2298–2318.
- Trnka, M., Hlavinka, P., Semenov, M.A., 2015. Adaptation options for wheat in Europe will be limited by increased adverse weather events under climate change. *J. R. Soc. Interface* 12, 112.
- Van Bussel, L.G., Grassini, P., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., De Groot, H., Saito, K., Cassman, K.G., Van Ittersum, M.K., 2015. From field to atlas: upscaling of location-specific yield gap estimates. *Field Crops Res.* 177, 98–108.
- Van Diepen, C., Wolf, J., Van Keulen, H., Rappoldt, C., 1989. WOFOST: a simulation model of crop production. *Soil Use Manag.* 5, 16–24.
- Van Grinsven, H.J.M., Spiertz, J.H.J., Westhoek, H.J., Bouwman, A.F., Erismann, J.W., 2014. Nitrogen use and food production in European regions from a global perspective. *J. Agric. Sci.* 152, 9–19.
- Van Ittersum, M., De Vries, S., Van Oort, P., Grassini, P., 2016a. Estimation of global yield gaps and implications from their analysis. *International Fertiliser Society. Proceedings* 795, 20. www.fertiliser-society.org ISBN 978-0-85310-432-2.
- Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. *Field Crops Res.* 143, 4–17.
- Van Ittersum, M.K., Van Bussel, L.G.J., Wolf, J., Grassini, P., Van Wart, J., Guilpart, N., Claessens, L., De Groot, H., Wiebe, K., Mason-D’Croz, D., Yang, H., Boogaard, H., Van Oort, P.A.J., Van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016b. Can sub-Saharan Africa feed itself? *Proc. Natl. Acad. Sci.* 113, 14964–14969.
- Van Wart, J., Van Bussel, L.G., Wolf, J., Licker, R., Grassini, P., Nelson, A., Boogaard, H., Gerber, J., Mueller, N.D., Claessens, L., 2013. Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crops Res.* 143, 44–55.
- Velthof, G., Oudendag, D., Witzke, H., Asman, W., Klimont, Z., Oenema, O., 2009. Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. *J. Environ. Qual.* 38, 402–417.
- Velthof, G., Lesschen, J., Webb, J., Pietrzak, S., Miatkowski, Z., Pinto, M., Kros, J., Oenema, O., 2014. The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000–2008. *Sci. Total Environ.* 468, 1225–1233.
- Webb, J., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, P., Reid, J., 2013. An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure-N efficiency. In: Sparks, D.L. (Ed.), *Adv. Agron. Academic Press*, pp. 371–442.
- Wolf, J., Hessel, R., Boogaard, H., De Wit, A., Akkermans, W., Van Diepen, C., 2011. Modeling winter wheat production across Europe with wofost—the effect of Two New zonations and two newly calibrated model parameter sets. In: Ahuja, L.R., Ma, L. (Eds.), *Methods of Introducing System Models into Agricultural Research*. American Society of Agronomy. Crop Science Society of America, Soil Science Society of America, Madison, WI, pp. 297–326.
- You, L., Wood-Sichra, U., Fritz, S., Guo, Z., See, L., Koo, J., 2014. Spatial Production Allocation Model (SPAM) 2005 v2. 0. Available at Mapspam. Info, 2015.