Field Crops Research 143 (2013) 130–142

Contents lists available at SciVerse ScienceDirect

Field Crops Research

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

A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union

Hendrik Boogaard[b,*], Joost Wolf[a], Iwan Supit[c], Stefan Niemeyer[d], Martin van Ittersum[a]

[a] Wageningen University, Plant Production Systems Group, P.O. Box 430, 6700 AK Wageningen, The Netherlands
[b] Alterra Wageningen UR, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands
[c] Wageningen University, Earth System Science Group, Wageningen, The Netherlands
[d] Joint Research Centre, European Commission, Institute for Environment and Sustainability MARS-AGRI4CAST, Ispra, Italy

ARTICLE INFO

Article history:
Received 18 July 2012
Received in revised form 1 November 2012
Accepted 6 November 2012

Keywords:
CGMS
Crop growth modelling
Triticum aestivum L.
WOFOST
Yield gap
Yield potential

ABSTRACT

Wheat is Europe's dominant crop in terms of land use in the European Union (EU25). Most of this wheat area is sown in autumn, i.e., winter wheat in all EU25 countries, apart from southern Italy, southern Spain and most of Portugal, where spring wheat varieties are sown in late autumn. We evaluated the strengths and limitations of a regional implementation of the crop growth model WOFOST implemented in the Crop Growth Monitoring System (CGMS) for calculating yield gaps of autumn-sown wheat across the EU25. Normally, CGMS is used to assess growing conditions and to calculate timely and quantitative yield forecasts for the main crops in Europe. Plausibility of growth simulations by CGMS in terms of leaf area, total biomass and harvest index were evaluated and simulated yields were compared with those from other global studies. This study shows that water-limited autumn-sown wheat yields, being the most relevant benchmark for the largely rain fed wheat cultivation in Europe, are plausible for most parts of the EU25 and can be used to calculate yield gaps with some precision. In parts of southern Europe unrealistic simulated harvest index, maximum leaf area index and biomass values were found which are mainly caused by wrong values of phenology related crop parameters. Furthermore CGMS slightly underestimates potential and water-limited yields, which calls for a calibration using new field experiments with recent cultivars. Estimated yield gap is between 2 and 4 t ha^{-1} in main parts of the EU25, is smaller north-western Europe and highest in Portugal.

1. Introduction

The European Union is a large food consumer and producer. Population growth, dietary changes (in particular, an increase in meat consumption) and increasing demand for bio-fuels (Godfray et al., 2010) are expected to result in a need for increasing crop production. Generally, in Europe actual yields are high and the gap between potential or water-limited yields and actual yields is relatively limited. Nevertheless it is important to identify regions where and to what extent crop yields can still increase.

Various approaches to determine global yield gaps exist (cf. Van Ittersum et al., 2013; Lobell et al., 2009). Neumann et al. (2010) applied a stochastic frontier production function to calculate global datasets of maximum attainable yields. Licker et al. (2010) evaluated attainable crop yields in different climates around the world by comparing yield patterns within regions of similar climate. Penning De Vries et al. (1997), Rabbinge and Van Diepen (2000), Fischer et al. (2002) and Nelson et al. (2010) simulated potential crop yields (using process based models) which were subsequently compared to actual yields.

Many crop simulation studies at global scale did not focus on potential or water-limited yields but on actual crop yield levels (Stehfest et al., 2007; Liu et al., 2007; Parry et al., 1999, 2004; Deryng et al., 2011; Bondeau et al., 2007). As such, results of these studies cannot be used for determining and benchmarking a yield gap. Global, model-based studies follow a top-down grid based strategy using global data sets of monthly weather (usually interpolated to daily data), crop and soil data fed into generic crop models with hardly any local calibration and validation of the models. While these studies lack inclusion of locally relevant information and factors that can influence yield potential, they have the advantage of global spatial coverage and using a consistent method worldwide, as opposed to many fragmented local studies, each with their own method (Lobell et al., 2009; Van Ittersum et al., 2013).

Van Ittersum et al. (2013) propose a bottom-up protocol for yield gap analysis that can be applied globally but has a strong local meteorological and agronomic basis. The protocol recommends (a)

* Corresponding author. Tel.: +31 317481635; fax: +31 317419000.
E-mail addresses: hendrik.boogaard@wur.nl (H. Boogaard), joost.wolf@wur.nl (J. Wolf), iwan.supit@wur.nl (I. Supit), stefan.niemeyer@jrc.ec.europa.eu (S. Niemeyer).

0378-4290/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fcr.2012.11.005

the use of well-calibrated crop growth simulation model applied to zones with a relatively homogenous climate, (b) the use of measured weather data, (c) the simulations to be done for the dominant soil types and cropping systems considering the current spatial crop distribution, (d) the use of site-specific agronomic and actual yield information, (e) empirical verification at the local level of estimated yield gaps with on-farm data and experiments and (f) explicit methods for up scaling.

We used the crop growth model WOFOST implemented in the Crop Growth Monitoring System (CGMS) to estimate the yield gap of wheat sown in autumn (autumn-sown) across the European Union (EU25).[1] Autumn-sown wheat is Europe's main crop in terms of area (around 18 million ha in the EU25); it stands for winter wheat in most of the EU25, apart from southern Italy, southern Spain and most of Portugal where spring wheat varieties are sown in late autumn. CGMS relies on local weather, soil and crop data as much as currently available as recommended by Van Ittersum et al. (2013), but it has full spatial coverage so it does not require up scaling procedures. Normally, CGMS is applied to monitor growing conditions for the main crops over Europe on a regional scale (e.g., Supit et al., 2012, 2010; Baruth et al., 2008). It is an integral part of the MARS Crop Yield Forecasting System (MCYFS; Micale and Genovese, 2004; Lazar and Genovese, 2004; Genovese and Bettio, 2004) that provides the European Commission (EC) with timely and quantitative yield forecasts for the main European crops. In this paper we assess the strengths and limitations of CGMS to estimate yield gaps of autumn-sown wheat for the EU25.

2. Materials and methods

2.1. Actual wheat yields

Mean actual wheat yields over the EU25 have been derived from the FADN (farm accountancy data network[2]) database. FADN is a European system of sample surveys held each year to collect structural and accountancy data on farms. The aim is to monitor the income and business activities of agricultural holdings and to evaluate the impacts of the Common Agricultural Policy (CAP). The FADN surveys include only farms that exceed a minimum economic size (threshold) so as to cover the most relevant part of the agricultural activity of each EU Member State. Only data until 2006 could be obtained. We selected the period 1990–2006 to sufficiently capture inter-annual variability and extreme yields in both the actual and simulated yield series. The period is smaller for member states that joined the European Union after 1990 (e.g., Baltic States, Slovenia, etc.). Yields in the FADN database are not differentiated for winter and spring wheat.

Actual wheat yields in FADN are collected either per country (small countries) or departments or states (large countries) (Janssen et al., 2009) and are subsequently converted into to dry weight (assuming 16% moisture content) and averaged across all years. The FADN database does not distinguish between irrigated and rain fed crop yields. To allow a meaningful yield gap analysis for a rain fed and irrigated water regime we used information on the spatial distribution and level of irrigation (Siebert et al., 2007).

2.2. The WOFOST model

The crop growth simulation model WOFOST (Van Diepen et al., 1989; Supit et al., 1994; Boogaard et al., 1998) is the central component of CGMS. WOFOST[3] was originally developed to simulate crop yield for a single location where weather, soil and crop data are assumed homogeneous. It is a member of the family of Wageningen crop models (Van Ittersum et al., 2003; Bouman et al., 1996). WOFOST computes daily biomass accumulation and its distribution over crop organs during the growth period using a photosynthesis approach. Crop yield is simulated for the potential (Y_p) and the water-limited (Y_w) situation and is expressed in dry weight (0% moisture). Y_p is determined by temperature, day length, solar radiation and genetic characteristics assuming absence of any water or other stress factors. Y_w is also limited by water supply, and hence influenced by rainfall, soil type and field topography. Soil water dynamics in the rooted zone are simulated with a daily time step. For both Y_p and Y_w an optimal nutrient supply is assumed. Yield losses caused by pests, diseases, weed and/or extreme weather events are not considered. Vernalization is not implemented and crop growth and phenological development are therefore calculated from January 1 onwards. Crop growth simulation initiates at mean daily temperatures above 0 °C assuming an initial biomass representing the crop state after the cold winter period.

WOFOST has been applied to simulate production of the main annual crops over Europe under present (De Koning and Van Diepen, 1992; Supit et al., 2010) and future conditions (Wolf, 1993; Wolf and Van Diepen, 1995; Supit et al., 2012). It has also been used for regional land evaluation, yield potential, risk analysis and yield forecasting studies in Europe, Africa and China (Reidsma et al., 2009; Hengsdijk et al., 2005; Savin et al., 1997; Wu et al., 2006; Rötter et al., 1997; Rötter and Van Keulen, 1997). Modelling results from WOFOST have been validated versus experimental information in many studies (Boons-Prins et al., 1993; Wolf, 1993; Wolf and Van Diepen, 1995; Reidsma et al., 2009) and by way of model comparison exercises (Rötter et al., 2012; Palosuo et al., 2011; Eitzinger et al., 2012).

To apply WOFOST on a regional scale it has been incorporated in CGMS creating an environment to run WOFOST for every location with a unique set of weather, soil and crop characteristics. Weather and crop data are assumed to be homogeneous per grid cell of the 25 km × 25 km climate grid while the soil characteristics are assumed to be homogeneous per soil unit. By overlaying the 25 km × 25 km climatic grid, soil map and arable land cover map, simulation units are determined. Logically each simulation unit is a unique combination of the climatic grid cell and soil unit and is valid for arable land only. In the absence of a winter and spring wheat land use map, an arable land cover map is used which is based on the GLC2000 (Bartholomé and Belward, 2005). It combines several classes of the GLC2000 into one arable land class.

2.3. Input data for CGMS

Historical weather data, i.e., daily values of maximum and minimum temperature, wind speed, global radiation, vapour pressure and precipitation are interpolated from station data to a 25 km × 25 km climatic grid (Beek et al., 1992; Van der Voet et al., 1993). These station data have been collected from the Global Telecommunication System (GTS) of the World Meteorological Organization as well as from national and sub national station networks. Presently, data from nearly 7000 stations are available. Of these stations about 2500 receive daily meteorological information. From 1975 a more or less complete European coverage is available. A simple interpolation procedure method was selected because of its ease to automate and its fast performance while

[1] We use the term EU25 though Malta and Cyprus are not included as these countries are not relevant for a winter wheat yield gap analysis.

[2] http://ec.europa.eu/agriculture/rica/.

[3] http://www.wofost.wur.nl/UK/documentation/.

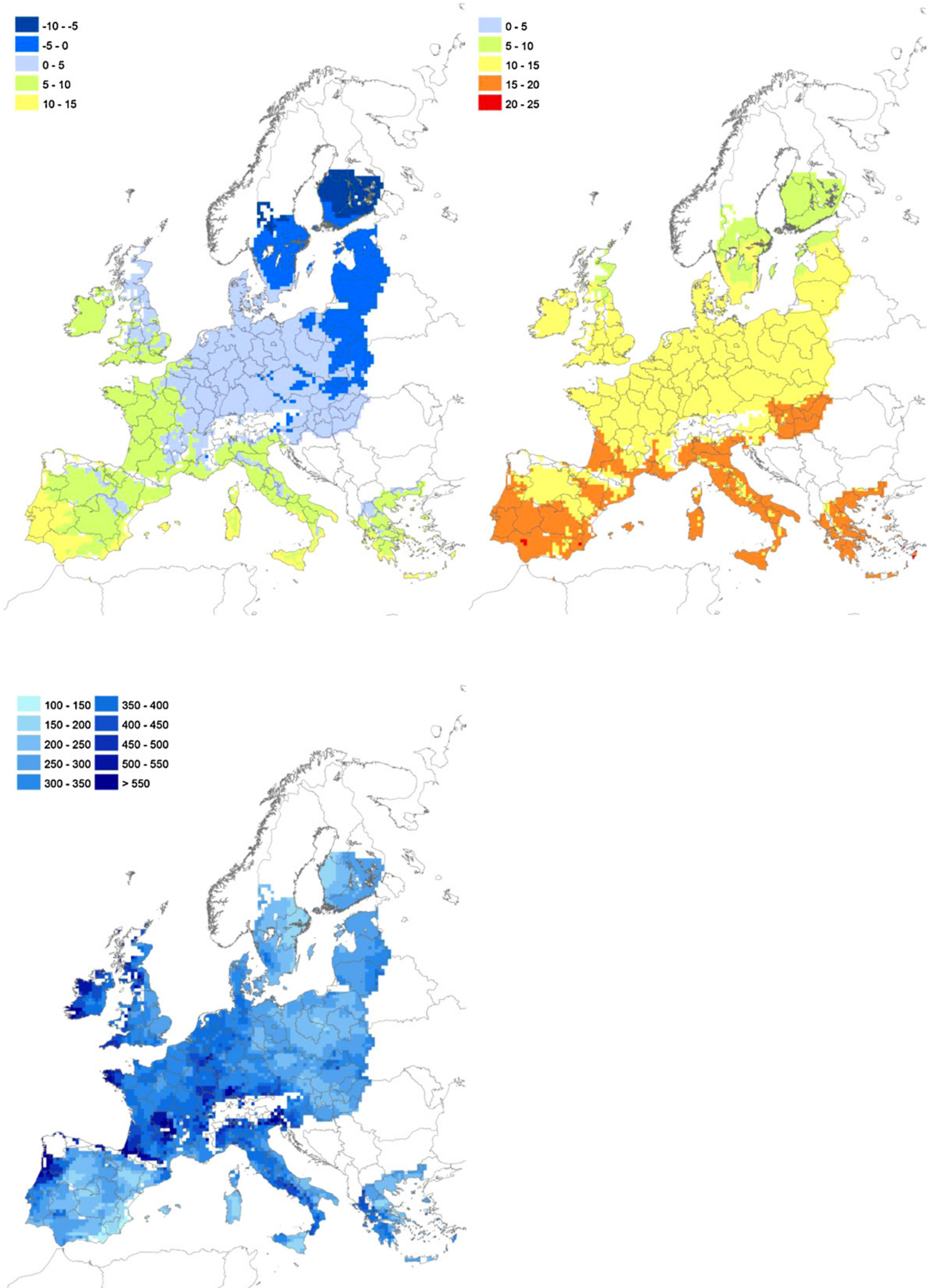

Fig. 1. Climate characteristics of grid cells of arable land map: long term daily mean temperature (°C) in January–March (upper left) and April–June (upper right) and long term precipitation sum (mm) over January–June (bottom). (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

Source: MARS Crop Yield Forecasting System of the European Commission.

maintaining sufficient accuracy as input to the crop growth model (Gozzini et al., 2000; Beek et al., 1992). Interpolation is executed in two steps: first the selection of suitable meteorological stations to determine representative meteorological conditions for a specific climatic grid cell. Second, a simple average is calculated for most of the meteorological parameters, with a correction for the altitude difference between the station and climatic grid cell centre in case of temperature and vapour pressure. As an exception precipitation data are taken directly from the most representative station. Mean daily temperature and precipitation sum over the growing season are shown in Fig. 1.

Crop parameter values for CGMS have initially been compiled by Van Heemst (1988) and calibrated by Van Diepen and De Koning (1990). In the framework of the MARS project Boons-Prins et al. (1993) have collected field experimental data from the United Kingdom, The Netherlands and Belgium to calibrate leaf area dynamics and yield levels. Moreover, crop phenology data was collected and reviewed (Russell and Wilson, 1994; Narciso et al., 1992; Hough, 1990) over western and southern Europe to determine region specific, phenology related crop parameters (temperature sums) used by the model to simulate flowering and maturity. During the late nineties Willekens et al. (1998) updated these temperature sum parameters at 50 km × 50 km grid and extended the spatial coverage to countries in MAGRHEB (central and eastern Europe and Turkey).

The 1:1,000,000 EU soil map and data base version 4.0 is used to supply the spatial distribution of the soil mapping unit (SMU), the composition of soil typologic units (STU) within each SMU and the soil properties of each STU (Baruth et al., 2006). For each STU CGMS requires the potential rooting depth and water retention properties (volumetric soil moisture content at wilting point, field capacity and saturation) to calculate a soil water balance. The spatial scale of the soil map is sufficiently detailed to reveal variability of water-limited yields due to different soils within a 25 km × 25 km climatic grid cell.

Simulated potential and water-limited yields are aggregated to the administrative regions of the European Union, the so-called NUTS[4] regions. Four NUTS levels, 0–3 are used, 0 being the national and 3 the smallest sub-regional level. Historical data on planted area on all NUTS levels originate from EUROSTAT (2005). The aggregation from simulation units to NUTS3 uses area weights taken from the arable land cover map while the aggregation from NUTS3 to NUTS2, NUTS 1 and NUTS 0 are based on planted area from EUROSTAT (2005).

2.4. Autumn-sown wheat growth modelling and evaluation

In this paper we focus on wheat crops that are sown in autumn varying from August in northern Europe to late November in southern Europe. For all simulation units besides potential (Y_P) and water-limited dry weight yields (Y_W), the total above-ground biomass at harvest (BIOM, dry matter in t ha^{-1}), the harvest index (HI, equal to grain yield dry matter/BIOM) and the maximum value for leaf area index (LAI-max, m^2 leaf area m^{-2} land area) during the growing period were saved for the period 1990–2006. The plausibility of the growth simulations was evaluated by comparing BIOM, HI and LAI-max. In addition, the simulated anthesis and maturity dates and the relative crop transpiration (i.e., actual evapo-transpiration over potential evapo-transpiration) for the water-limited production situation were used to evaluate the simulations. Note, that it is not possible to rigorously calibrate crop parameters of CGMS for all simulations units (around 16,000).

[4] http://ec.europa.eu/eurostat/ramon/nuts/codelist_en.cfm?list=nuts.

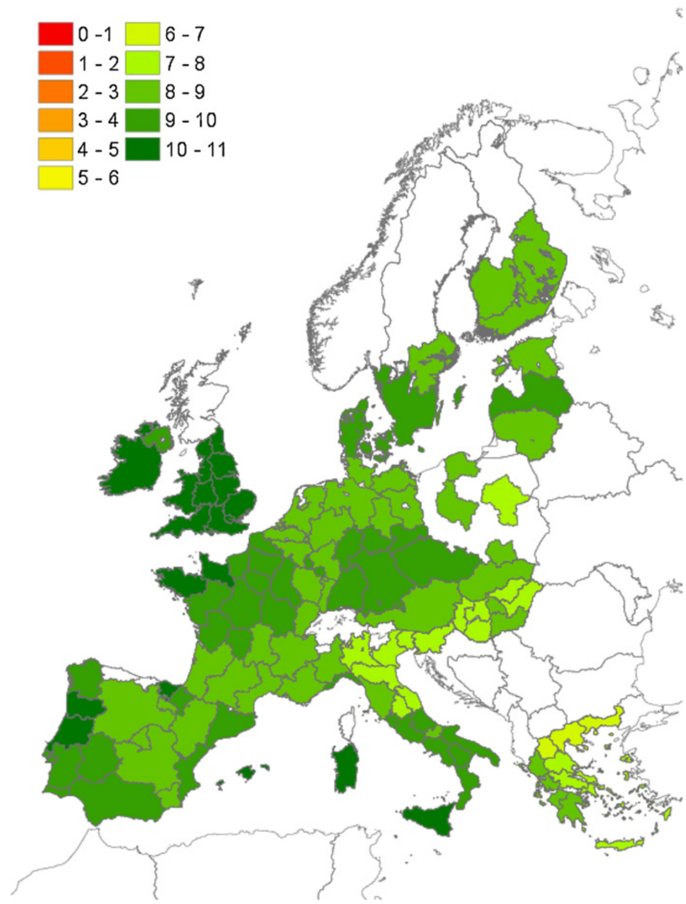

Fig. 2. Simulated potential autumn-sown wheat yields (dry matter; t ha^{-1}). (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

Though phenology related parameters have been updated for local weather and regional crop calendars at a 50 km × 50 km grid (Section 2.3) other crop parameters related to leaf area dynamics and yield level have been extrapolated from crop parameters sets calibrated for a limited number of sites in Western Europe. In addition to the above quality checks we compared the potential and water-limited yields and yield gaps with results of other studies.

3. Results from CGMS calculations

3.1. Potential yields

Due to moderate differences in climate, potential autumn-sown wheat yields show a limited variation over the EU25 (8–11 t ha^{-1}, see Fig. 2). Highest potential yields mainly occur in Ireland, UK, western France, areas that have a long growing period with relatively low spring and summer temperatures as a result of a strong maritime influence. Portugal and southern regions of Spain and Italy also have high potential yields due to mild winter temperatures. Lowest potential yields (below 8 t ha^{-1}) are found in north-eastern Italy, Slovenia and northern Greece.

Fig. 3 shows the simulated anthesis and maturity dates. Anthesis dates increase from south to north: around March 20 in southern Spain to July 10 in southern Scandinavia. The maturity dates show the same pattern: around June 10 in southern Spain to August 30 in northern Europe. Logically, simulated anthesis and maturity dates closely resemble the observed crop calendars that were used to determine region specific temperatures sum parameters used in CGMS.

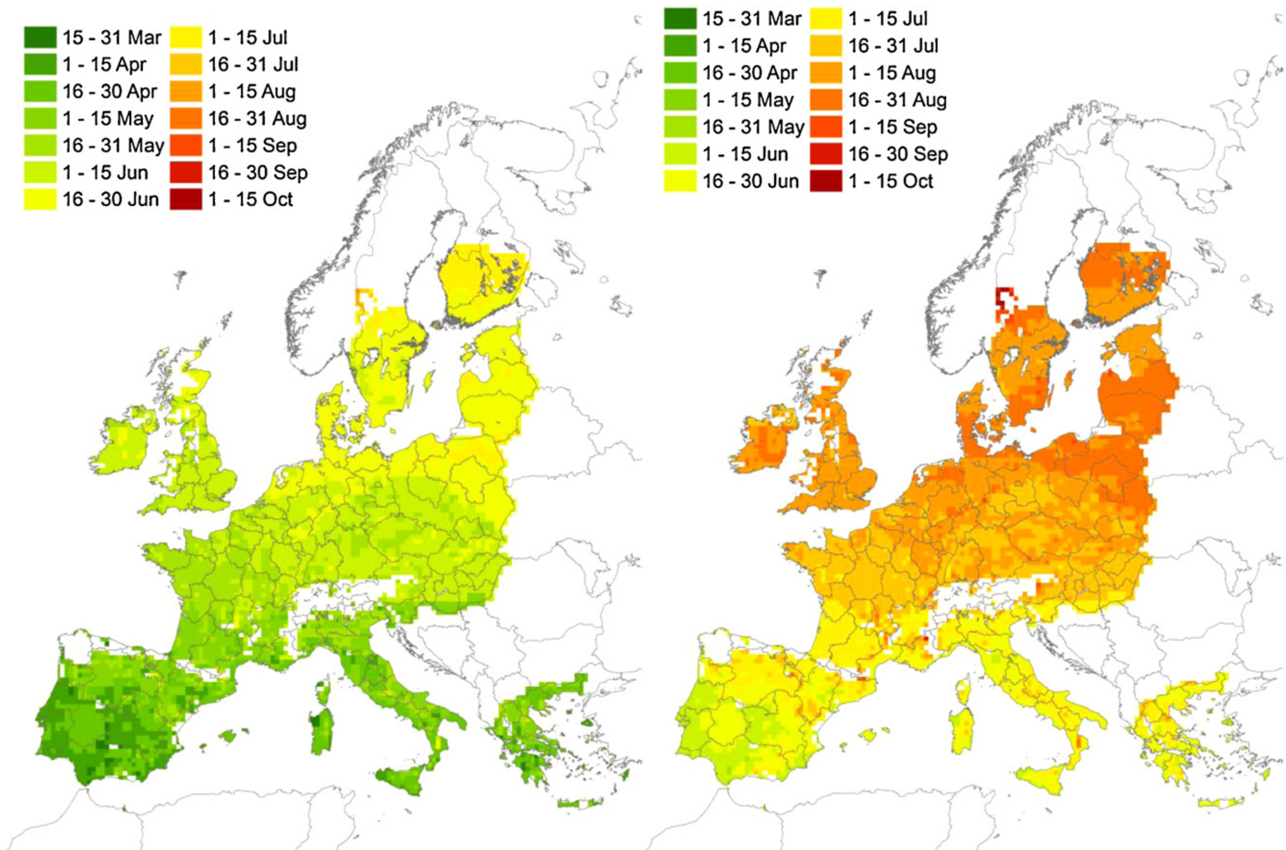

Fig. 3. Simulated dates of crop anthesis (left) and maturity (right) for autumn-sown wheat. (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

Three crop characteristics (BIOM, HI and LAI-max, see Fig. 4) are used to evaluate the plausibility of the potential yields. Under optimal growing conditions we expect a BIOM between 16 and 22 t ha^{-1}, a HI between 0.40 and 0.60, and a LAI-max between 4 and 7 (Boons-Prins et al., 1993; Groot and Verberne, 1991; information from Dutch winter wheat variety trials[5]). LAI-max values fall in the expected range over the main part of Europe (Fig. 4). Slightly higher values are observed in temperate climate areas along the coast and lower values are found in cool areas (e.g., in Sweden) and in continental climate areas, resulting in a lower light interception and thus a reduced growth. Significantly lower values occur in some areas in central-eastern Spain, southern France, central Italy, Slovenia and Greece. These areas appear to have a value too low for the model parameter that determines the duration between 1st January and anthesis, resulting in a short simulated period of leaf formation and thus a low simulated LAI-max and light interception. In few areas (mainly small areas in central-eastern Spain) with a strong continental climate, simulated LAI-max and BIOM appear to be very low. Average daily temperatures in spring are between 5 and 10° leading to continuous on-going crop development. However the minimum temperature is often close to or below zero which completely stops assimilation. This is caused by a model function describing the transformation of assimilates into structural biomass during night. If low minimum temperatures prevail for a several days, assimilates accumulate and the assimilation rate diminishes and ultimately halts (Supit et al., 1994). In reality, wheat varieties that are grown in these areas are probably better adapted (than assumed in this model function) for these continental conditions.

Highest BIOM (>20 t ha^{-1}) values occur in coastal regions (e.g., Ireland, UK, western France, Portugal, and Denmark) as a result of a long growth period that is caused by relatively mild winter and low summer temperatures. Lower values (15–20 t ha^{-1}) have been simulated for main parts of the EU25 and relate to the shorter growing period caused by either the continental climate (cold spring and warm summers) or Mediterranean climate (warm summers). The lowest BIOM values (<15 t ha^{-1}) occur in the same areas for which the LAI-max (and thus the light interception and growth rate) are low. HI is within the expected range (0.40–0.60) in major parts of the EU25 and is only very high (>0.60) in the areas with extremely low values of LAI-max and BIOM. In these areas the period of leaf and stem formation is too short compared to the period of grain formation leading to high values for HI.

3.2. Water-limited yields

The main part of the EU25 has water-limited yields between 7 and 9 t ha^{-1} (Fig. 5) and these are 1–2 t ha^{-1} lower than potential yields. This small difference indicates that water stress during the growing period is limited and that climatic conditions in winter and spring are rather humid in most regions over the EU25. Highest water-limited yields (8–11 t ha^{-1}), being almost similar to the potential yields, mainly occur in Ireland, western England, Scotland, and western France. These regions all have a relatively high rainfall and a very long growth period for winter wheat due to mild

[5] http://www.kennisakker.nl/kenniscentrum/document/rassenbulletin-wintertarwe.

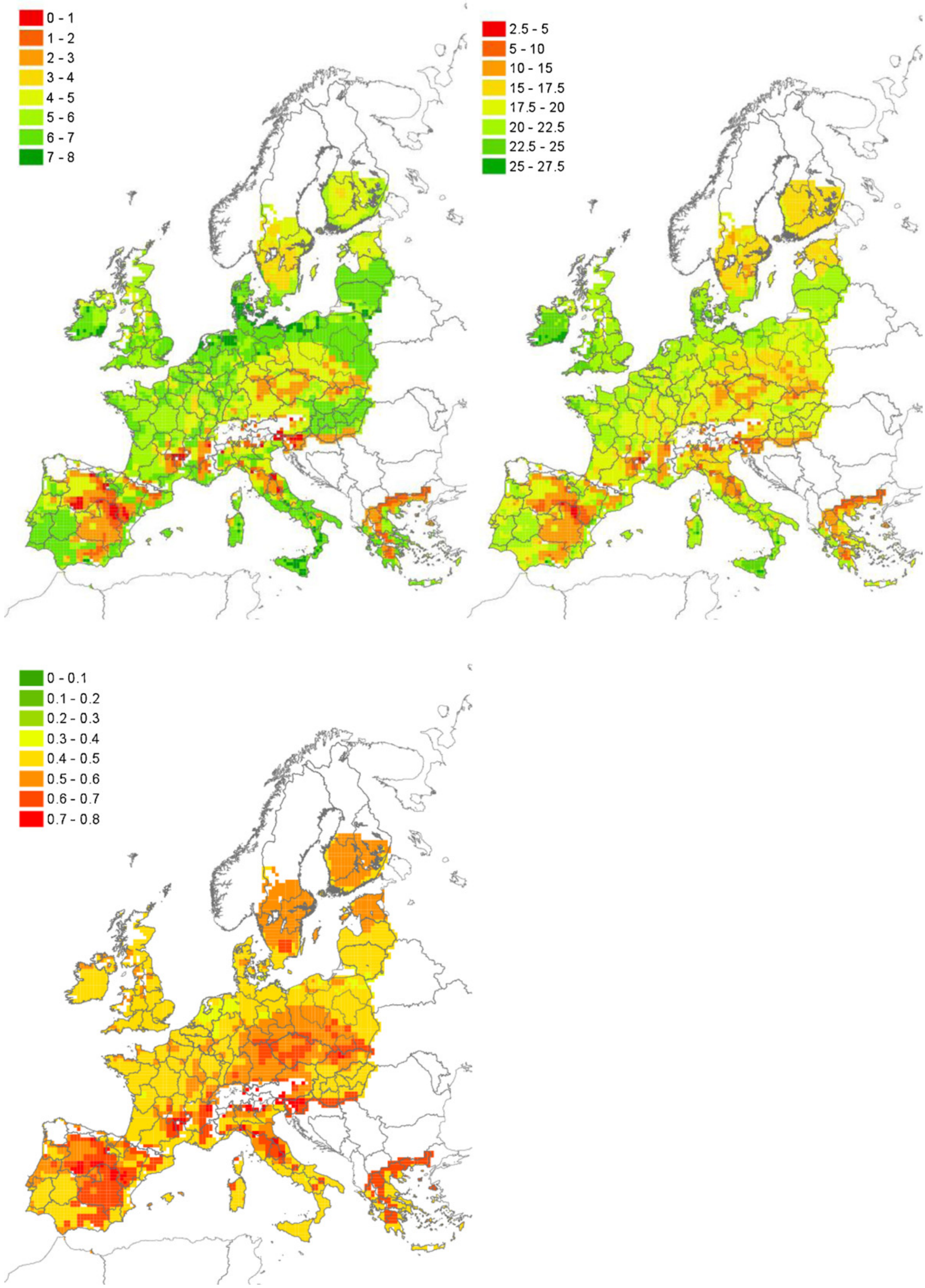

Fig. 4. Maximum leaf area index (LAI-max, in ha ha^{-1}, upper left), total biomass (BIOM, dry matter in t ha^{-1}, upper right) and harvest index (HI, in –, lower left) for simulated potential growth and production of autumn-sown wheat. (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

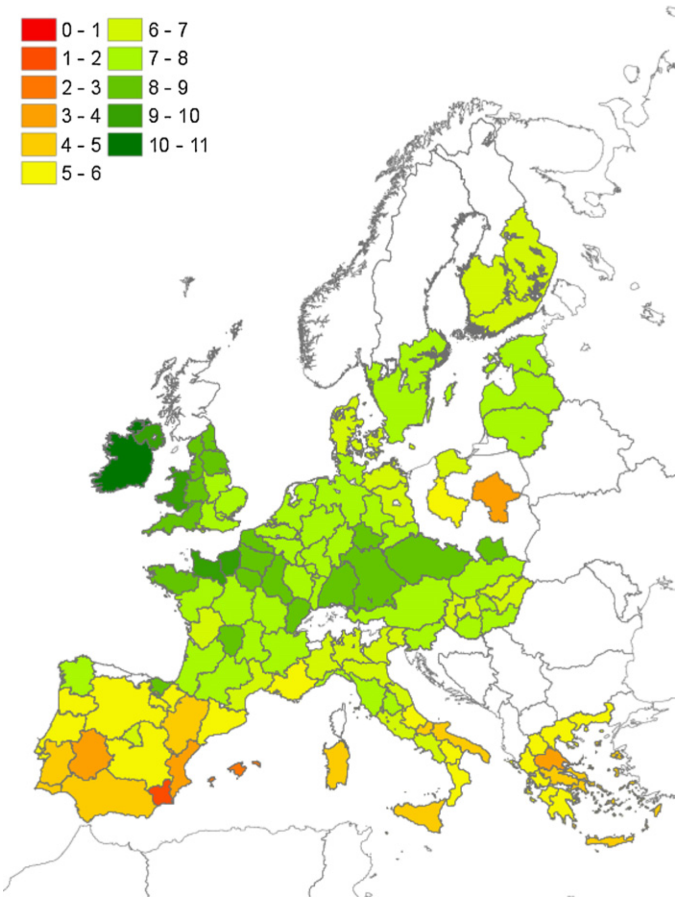

Fig. 5. Simulated water-limited autumn-sown wheat yields (dry matter; t ha^{-1}). (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

winters and relatively low summer temperatures, both as a result of a strong maritime influence. Lowest water-limited yields (1–5 t ha^{-1}) are found in parts of Spain, southern Italy, Greece and Poland due to both the relatively short growth period and the low-rainfall.

For all countries the LAI-max for water-limited conditions appear to be practically similar to those under potential growing conditions (Fig. 6), which indicates that growth reduction due to drought mainly happens during the grain filling period in our simulations. Highest values of BIOM (>20 t ha^{-1}) do occur in regions and countries along the coast (e.g., Ireland, western England, Scotland, and western France) where LAI-max values are almost similar to potential values for BIOM. This is plausible as the rainfall in these regions is relatively high. Lowest values are found in the hot and dry areas in Europe (i.e., between 5 and 15 t ha^{-1} in Spain and Greece) caused by a lack of rainfall and a short growth period. HI is between 0.40 and 0.60 in main parts of the EU25, but is very low (<0.30) in, for example, south-western Spain and southern Italy and very high (>0.60) in the same areas where the LAI-max and BIOM values under potential conditions are extremely low (Section 3.1).

The relative crop transpiration (RTRA, i.e., actual ET/potential ET; Fig. 6) indicates to what extent water-limited yields and BIOM are affected by drought. High RTRA values (1–0.9) are correlated to high seasonal rainfall sums in coastal zones and mountainous regions. In some dry southern regions (i.e., central-eastern Spain and northern Greece, see Fig. 6) RTRA approaches unity which is an artefact and is caused by the extremely low LAI-max and BIOM values and its limited water demand by ET (Section 3.1). Lower RTRA values (0.2–0.7) in southern Europe (and for instance Poland) indicate major drought stress and these low values correspond to low HI values in the same regions (Fig. 6). Drought stress mainly occurs during grain filling and then leads to relatively low grain yields compared to BIOM and thus low HI values.

4. Actual yields and yield gap

Highest actual dry matter wheat yields (between 6 and 8 t ha^{-1}) are found in north-western Europe (Fig. 7). In most regions of the EU25 yields vary between 4 and 6 t ha^{-1}. Lowest yields (<3 t ha^{-1}) occur in Spain, southern Italy and Greece because of the hot and dry conditions in spring. In Finland and the Baltic States spring wheat (sown in spring) is predominantly cultivated which results in relatively low actual yields. For most European countries the spring wheat area covers less than 20% of the wheat area. Except for Finland and the Baltic States, the FADN database mainly represents autumn-sown wheat.

Yield gaps for wheat must be calculated against potential yields for irrigated areas and water-limited yields for rain fed areas (Fig. 8). Although intensive irrigation (>50% of area, see Fig. 9) occurs in various basins, irrigation water is used mainly for cash crops (e.g., vegetables, fruits) and summer crops (rice and maize) (MMA, 2007). Crops such as wheat are grown mainly under rain fed conditions. In other intensively cropped areas, such as Denmark, The Netherlands, central Portugal and southern France, between 10 and 30% of the arable crops are irrigated, whereas in other regions over Europe, the irrigated fraction of arable land is less than 10%. This indicates that in most regions the yield gap can be based best on the simulated water-limited yields minus the actual yields.

Yield gap estimations based on simulated water-limited yields are generally 2–4 t ha^{-1}, but smaller (0–2 t ha^{-1}) in north-western Europe (Fig. 8). The highest yield gaps (>4 t ha^{-1}) are calculated for Portugal and the Baltic states and Finland (note that the actual yields in the Baltic states and Finland generally represent the lower yielding spring-sown wheat). Negative yield gaps relative to water-limited yields occur (0 to −1 t ha^{-1}) in the coastal areas near Valencia. This indicates that in these areas the water supply is less limiting than assumed in the simulation which might be due to irrigation. The Netherlands, Denmark and North Germany have very small yield gaps, likely because of capillary rise of groundwater not included in the simulations (Fig. 8). Remarkably low yield gaps are found in Poland which is probably due to an underestimation of the simulated water-limited yield. Furthermore the yield gap in some areas in Spain, southern France, central and southern Italy, Slovenia and Greece is probably larger for both irrigated and rain fed conditions due to reasons explained in Sections 3.1 and 3.2 (CGMS probably underestimates yields due to wrong crop parameter values).

5. Discussion

Uncertainty of the yield gap estimates depends on the actual yield data and on the simulated potential and water-limited yield data. In the following sections the uncertainty of each of these variables is discussed. Finally the CGMS approach to calculate the yield gap of autumn-sown wheat is compared with other studies.

5.1. Uncertainty in actual yields

The FADN system is the best possible source on actual wheat yields available in Europe. These actual yields represent farmers' yields fairly well as the total number of farms included in FADN per year exceeds 74,000 for the EU25. Separate statistics on wheat varieties are lacking in the FADN database. For most countries this is not a problem as, compared to winter wheat, spring wheat area is

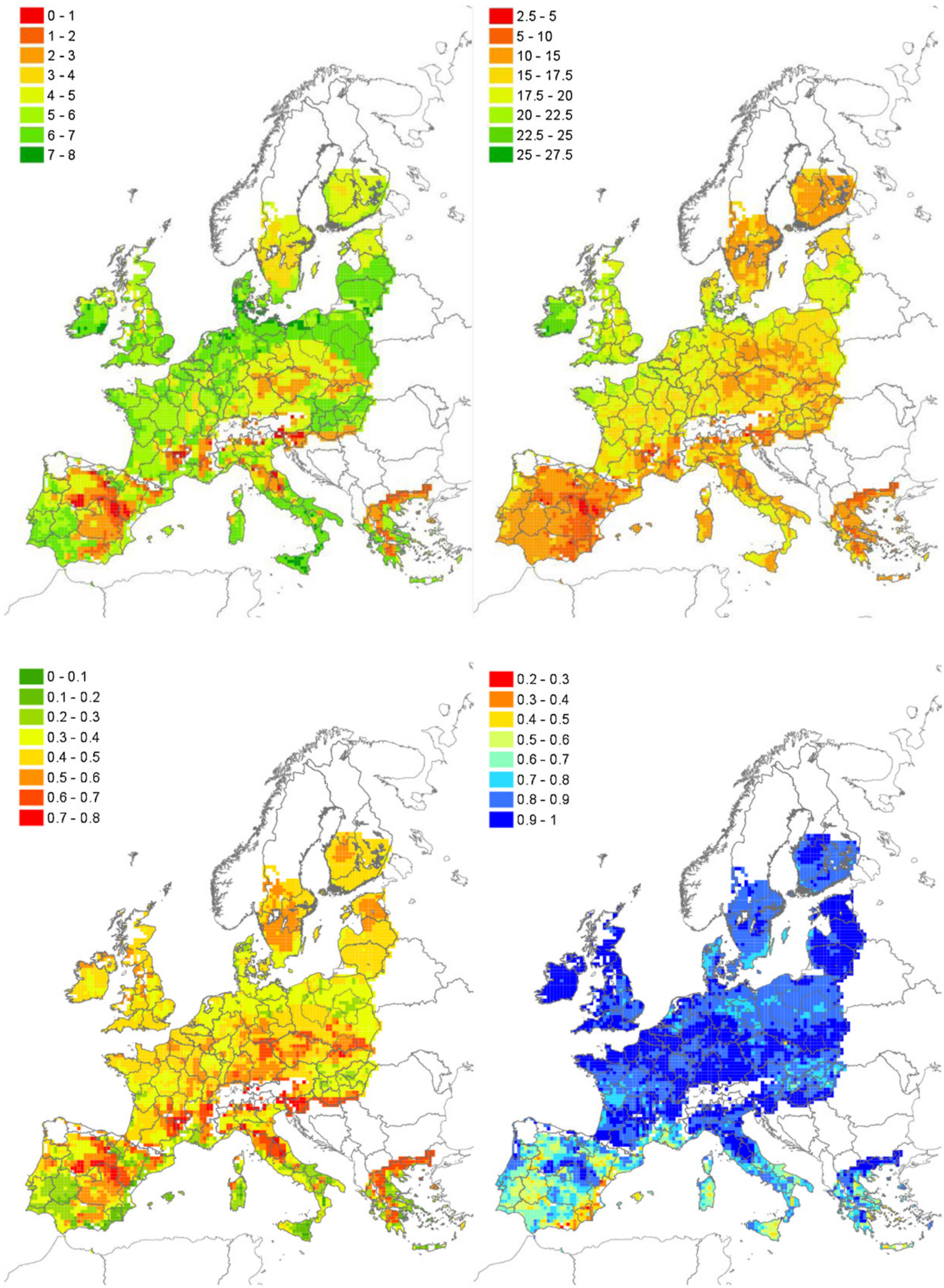

Fig. 6. Maximum leaf area index (LAI-max, in ha ha^{-1}, upper left), total biomass (BIOM, dry matter in t ha^{-1}, upper right), harvest index (HI, in –, lower left) and the relative crop transpiration (RTRA, i.e., actual/potential ET, lower right) for simulated water-limited growth and production of autumn-sown wheat. (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

negligible. Exceptions are Finland and the Baltic states where spring wheat (sown in spring) is the dominant wheat variety. Compared to autumn-sown crops (winter wheat and autumn-sown spring wheat), spring-sown crops have significantly lower yields which make the FADN wheat yields of these countries not suitable for yield gap analysis. Furthermore the FADN database does not distinguish between rain fed and irrigated wheat yields. In case of wheat this is likely to be a small problem as almost all wheat in the EU25 is

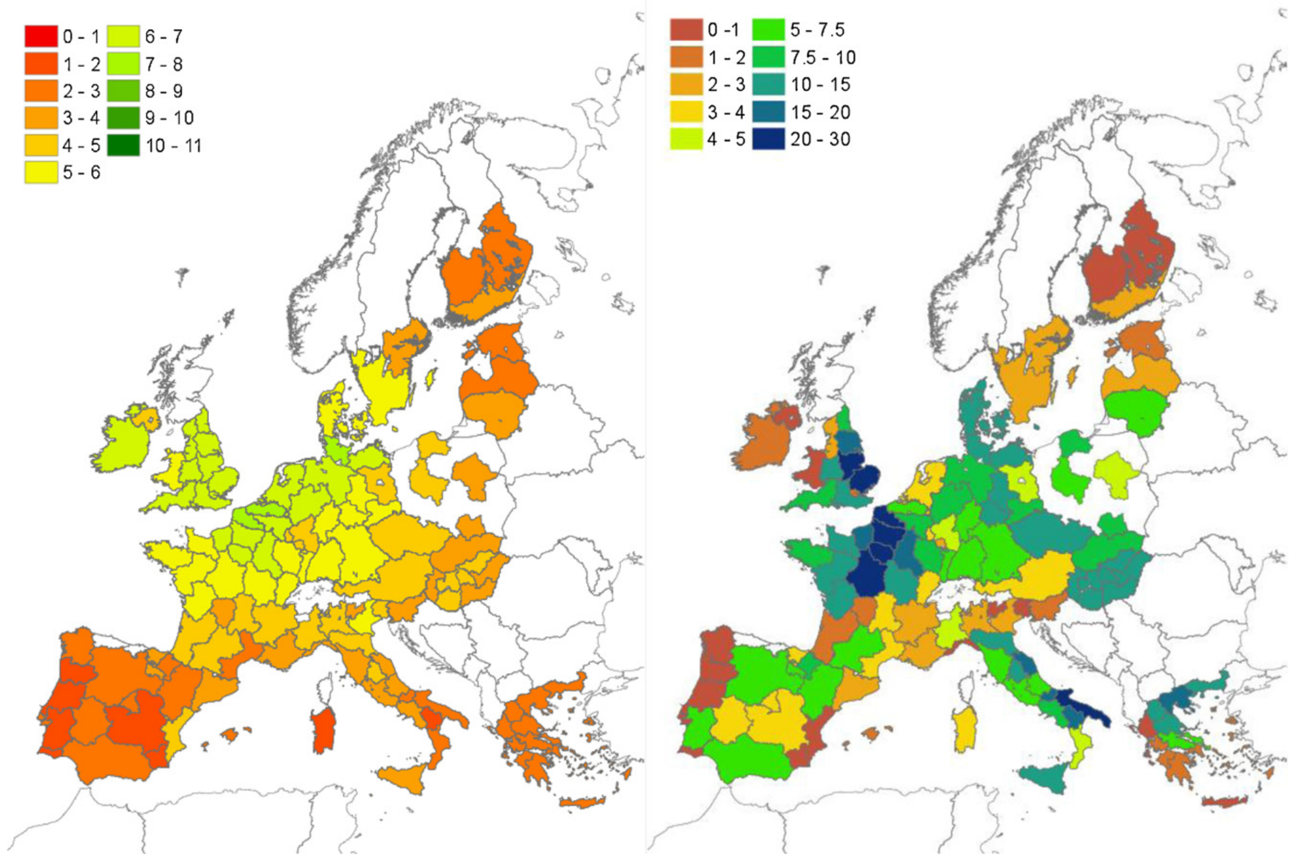

Fig. 7. Actual yields (dry matter; t ha^{-1}, left) and autumn-sown wheat areas taken from EUROSTAT (2005) (in % of total land area, right). (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

rain fed (e.g., MMA, 2007). Yet, for other, more commonly irrigated, crops (e.g., grain maize) the FADN database seems less appropriate for correct estimations of yield gaps. FADN data are only available at NUTS level 2 (NUTS level 1 or 0 in case of smaller countries), which thus defines the finest level at which yield gaps can be estimated with this source.

Actual yields in this study might be (slightly) underestimated as wheat yields increased due to adoption of improved technology (Fischer and Edmeades, 2010). We took the average actual yield over 1990–2006. 2006 is the most recent year with sufficient data available. To capture inter-annual variability of water-limited yields Van Ittersum et al. (2013) recommend a period of at least 15 years for simulating water-limited yields and 10 years for actual yields in case of favourable, high-yield environments and longer time intervals (15–20 years) of actual yields for very harsh environments. We took the same period for both simulated water-limited yields and actual yields so that both time series include the same extreme yields.

5.2. Uncertainty in simulated potential and water-limited yields

Autumn-sown wheat yields as simulated with CGMS are plausible for most regions of the EU25. The use of a validated, process based crop model, WOFOST (within CGMS), driven by detailed input data results in plausible key crop characteristics such as BIOM, LAI-max and HI. However, for some regions in southern Europe unrealistic values of BIOM, LAI-max and HI indicate that simulated yields are not plausible. First, CGMS overestimates drought stress during the grain filling period resulting in relatively low HI values in the water-limited simulations (e.g., southern Spain, southern Italy). In reality, however, crops partly compensate for low assimilation rates during grain filling using earlier produced stem reserves (Kemanian et al., 2007; Slewinski, 2012), a process that is not accounted for in CGMS. The problem can be solved by calculating grain yields from simulated total biomass production times either a fixed HI or an HI that is related to the relative biomass accumulation after anthesis (Kemanian et al., 2007).

Second, too high HI values (and simultaneously, too low LAI-max and BIOM values) in the simulations are found in some areas in central-eastern Spain, southern France, central Italy, Slovenia and Greece and are caused by too low values of the temperature sum parameter that determines the time duration between 1st January and anthesis. Most important reason is the mismatch between the spatial scale of observed crop calendars and simulation units which especially applies to the more mountainous areas. The crop calendar data used to determine temperature sums between 1st January and anthesis (Russell and Wilson, 1994; Narciso et al., 1992; Hough, 1990; Willekens et al., 1998) mostly relate to administrative regions. Such calendars are averages for the main agricultural areas and ignore spatial variability within these regions. For instance, a regional crop calendar valid for a valley can be linked to a colder climatic grid cell representing a plateau while in reality the crop within this climatic grid cell has a later anthesis and maturity date than the valley. Besides, the latest update of temperature sum parameters in CGMS (Willekens et al., 1998) was done on a coarse spatial grid resulting in the assignment of relatively low temperature sum crop parameter values from the cooler higher altitude areas also to the warmer lowland areas. Third, very low simulated LAI-max and BIOM values occur in areas (mainly small areas in central-eastern Spain) with a strong continental climate. This can be explained from the negative effect of low minimum temperatures in spring on the assimilation rate (specifically the conversion

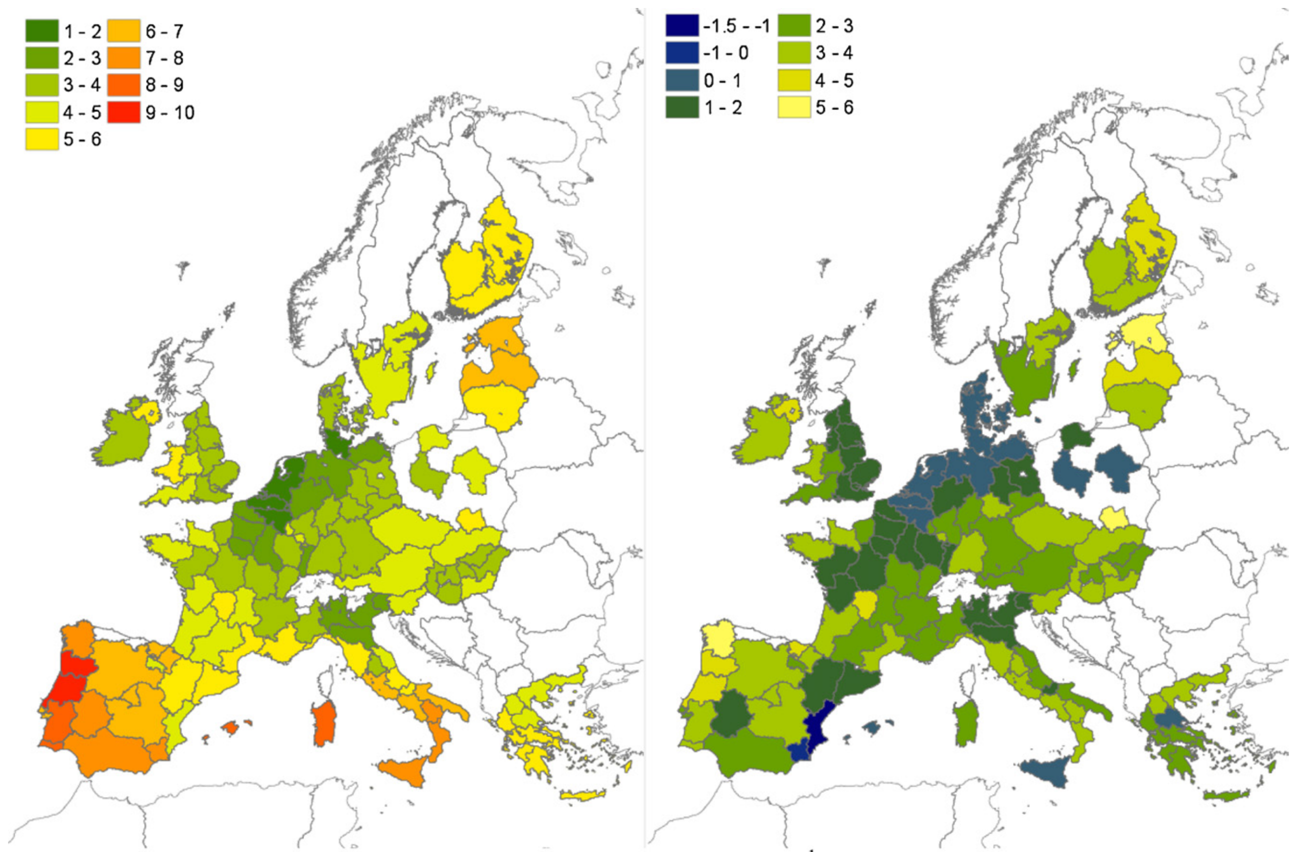

Fig. 8. Yield gap for autumn-sown wheat (dry matter; t ha^{-1}) as based on the difference between simulated potential yields for irrigated areas (left) and water-limited yields for rain fed areas (right) and actual wheat yields. (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

of assimilates in structural biomass during night), probably being less strong in reality than assumed in the growth simulations.

Recently the EC launched a study to compile and calibrate new parameter sets for the major arable crops over Europe, based on the most recently collected crop information (Wolf et al., 2011) and executed on the current 25 km × 25 km climatic grid. The use of this new set will solve several of the above mentioned problems and will improve the performance of CGMS, as this parameter set will better represent local variation in crop calendars and growing conditions. However the evaluation is still on-going and this new parameter set is not yet implemented in CGMS.

Calibration is another source of uncertainty. CGMS uses model parameters that are based on field data from wheat experiments in Western Europe during the 1980s (Van Diepen and De Koning, 1990; Boons-Prins et al., 1993). Improved new wheat varieties have higher potential yields (Fischer and Edmeades, 2010) and the potential yield levels presented in this study may therefore be lower than the latest potential yield levels. A new model calibration based on more recent wheat experiments is needed, however detailed crop experiments are nowadays carried out by private companies that often do not allow the use of their experimental data.

A third point of uncertainty with respect to simulated yields is related to the quality of the used input data for CGMS, in particular solar radiation, temperature and rainfall. According to Roerink et al. (2012) the CGMS global radiation values may be less accurate due to the different weather elements and methods used. Depending on data availability, global radiation values are a mixture of measured radiation and values based on either sunshine duration, cloud cover and temperature or only temperature (Supit and Van Kappel, 1998). Both the interpolation process (to a 25 km × 25 km grid), as well as the method to estimate radiation contribute to the uncertainty in the results. Roerink et al. (2012) recommend using the global radiation of MeteoSat Second Generation (Trigo et al., 2011) in CGMS. Also, in the absence of winter and spring wheat land use maps, an arable land cover map was applied. As a consequence, areas where autumn-grown wheat is grown have been overestimated and this introduced uncertainty in the aggregation of simulated yield to regional levels especially where climate and soil do vary within such region. Another uncertainty as to input data, refers to the available soil water at sowing that is set at field capacity in CGMS. For areas such as eastern Spain available water at sowing might be lower due to the relatively dry winter conditions (Supit and Wagner, 1998). Finally, due to a lack of input data (e.g., groundwater levels) calculation of capillary rise of groundwater has been switched off and thus CGMS may have underestimated water-limited yields for some regions (e.g., The Netherlands).

Uncertainty in simulation results is also caused by model simplifications. As explained re-allocation of assimilates across plant organs (from stems to grains) during drought is not included in CGMS. Further, vernalization is not implemented and crop growth simulation starts on 1st January (effectively when mean daily temperatures are above 0 °C after 1st January). In reality winter wheat is sown in autumn varying from August in northern Europe to November in southern Europe (in southern Italy, southern Spain and much of Portugal this autumn-sown wheat is a spring wheat variety). Initial biomass, representing the crop state after the (cold) winter period, is based on field experiments (Van Heemst, 1988; Van Diepen and De Koning, 1990). In CGMS spatial variation in initial biomass, resulting from spatial differences in autumn growth and winter conditions (damage due to frost), is not included as good data are not available. In the far south (e.g., around Seville) yields may be underestimated as wheat growth starts before 1st January

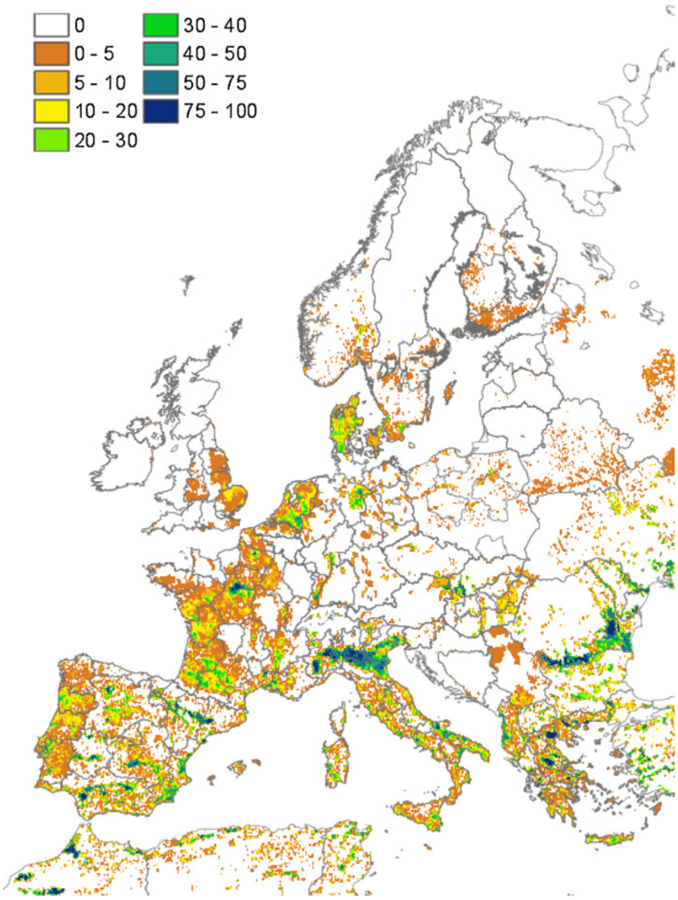

Fig. 9. Irrigated areas (as percentage of total land area) (Siebert et al., 2007). (For interpretation of the references to colour in this artwork, the reader is referred to the web version of the article.)

due to mild winter temperatures. Finally the soil moisture content is calculated by a simple two layer water balance model. The first layer is the actually rooted zone, which grows in thickness from an initial value of 10 cm to its maximum value, limited by soil depth or crop property. This concept has an undesired co-effect as the increase of soil moisture content due to rainfall depends on rooting depth. In some situations this leads to a very quick recovery of the crop after rainfall since all the roots have immediate access to infiltrating rain. A new version is being developed in which soil layers are at fixed positions (they do not grow downward with the roots) and water transport between layers is estimated from soil hydraulic conductivity as a function of the soil water content (Rappoldt et al., 2012), but this is not yet operational in CGMS.

5.3. Reliability of the yield gap estimates

Van Ittersum et al. (2013) report potential and actual winter wheat yields of different studies for the Netherlands. We compared these yields with CGMS and data from variety trials and added the study of Fischer et al. (2002) (Table 1). Potential yields given by Licker et al. (2010) are too low (lower than actual yields). On the contrary, yields of CGMS, Fischer et al. (2002) and Stehfest et al. (2007) are close to those of variety trials which can be regarded as a reliable reference for potential winter wheat yields in the Netherlands. As expected, the CGMS yields slightly underestimate potential yields for the Netherlands which emphasizes the need to calibrate for new varieties.

Apart from Neumann et al. (2010) and Fischer et al. (2002) most other studies focus on simulation of actual yields instead of potential or water-limited yields. The frontier yields of Neumann et al. (2010) are quite similar to the simulated water-limited yields of CGMS for France, Germany and UK (dry matter: 7–8 t ha^{-1}). They used a stochastic frontier production function on actual wheat yields to calculate global datasets of attainable yields for different agri-environmental conditions. For France, Germany and UK we can assume that these highest yields are approaching the biophysical limit of water-limited yields, as many farmers practice near-optimal crop management (nutrients non-limiting and biotic stress effectively controlled). For most areas in southern and central Europe, however, Neumann et al. (2010) show yield gaps (between 0 and 3 t ha^{-1} in fresh matter) that are considerable smaller than those of CGMS (between 3 and 6 t ha^{-1} in dry matter). These differences in estimated yield gap follow from differences between the two methodologies where the frontier yield (i.e., the highest observed yield) of Neumann et al. (2010) does not necessarily match the biophysical limit (Van Ittersum et al., 2013).

We also compared water-limited yields of CGMS with Fischer et al. (2002) for some major wheat producing countries in Europe (see Table 2). For France and Germany, yields of Fischer et al. (2002) are higher than in CGMS while for the United Kingdom Fischer et al. reported lower yields than CGMS that are also lower than the FADN actual yield. These low yields may can be explained by the aggregation method employed by Fischer et al. and the absence of a wheat land use map as these yields reflect the average of the high yielding regions in east England and low yielding areas in e.g. Scotland where Fischer et al. present results although the FADN database does not report any winter wheat. For Spain the CGMS water-limited yields are lower (1.5 t ha^{-1}) than Fischer et al. while spatial variability (visually checked) corresponds, i.e., lower yields in southern and eastern Spain and higher yields in Castilla y Leon. Section 5.2 provides reasons for too low simulations for parts of Spain.

The method presented in this study is based on existing and continuously updated information from the CGMS modelling system with autumn-sown wheat simulation results presented here as an example. In the near future, similar information will also come

Table 1
A comparison of potential and actual winter wheat yield (dry matter in t ha^{-1}) for The Netherlands collected from different studies.

	Relevant period	Potential yield[c]	Actual yield
CGMS	1990–2006	8.7	
Stehfest et al. (2007)[a]	1961–1990	9.5	
Licker et al. (2010)	1997–2003	6.3	
Variety trials[b]	2007–2011	9.6	
Fischer et al. (2002)	1961–1990	9.0	
Monfreda et al. (2008)	1997–2003		7.1
CBS, Statline (2012)	1994–2011		7.3
FADN data	1990–2006		6.9

[a] Because of the high fertilizer application rates and low water stress in the Netherlands this value can be used as an estimation of potential yield.
[b] Data from variety trials as provided by Bert Rijk, Wageningen University. (http://www.kennisakker.nl/kenniscentrum/document/rassenbulletin-wintertarwe).
[c] Note that Neumann et al. (2010) do not have data as for the Netherlands no grid cells were selected in their statistical approach.

Table 2
A comparison of water-limited autumn-sown wheat yield (dry matter in t ha^{-1}) as estimated by CGMS and Fischer et al. (2002) for some major producing countries in Western Europe.

	CGMS	Fischer et al. (2002)
Germany	7.5	9.3
France	7.8	8.9
United Kingdom	8.2	6.7
Spain	4.9	6.4

available for other continents since the EC is planning to set-up CGMS applications outside Europe.

Comparison with other studies and variety trials show that water-limited yields of CGMS are consistent and realistic and can be used to calculate yield gaps in the EU25. Unlike other global approaches CGMS combines a robust, validated crop growth model WOFOST with detailed input data that has a good spatial coverage. Spatial variation in climate, soil and crop are captured and as such regional estimates can be simply obtained by area weight aggregation. The approach proposed by Van Ittersum et al. (2013) invests in collecting agronomic data from local sites with wheat cultivation (including differences between autumn-sown and spring-sown wheat varieties, as well as soft and durum wheat cultivation) which might limit the number of these sites and as a consequence some variability in climate, soil and crop might be ignored in the aggregation to regional estimates.

6. Conclusions

CGMS simulates potential and water-limited yields and other simulated crop characteristics of autumn-sown wheat in a consistent and plausible manner for most regions in the EU25 and results can be used to calculate yield gaps with some precision. For most regions in the EU25 yield gaps for autumn-sown wheat can be based on simulated water-limited yields minus actual yields, except for areas with high groundwater levels, where potential yields are more representative. The yield gap is between 2 and 4 t ha^{-1} in main parts of the EU25, is smaller north-western Europe and highest in Portugal.

In some regions in southern Europe unrealistic values of harvest index, maximum leaf area index and biomass are simulated which are caused by wrong values of crop parameters (mainly phenology related) and the omission in CGMS to re-allocate assimilates from stems to storage organs during severe droughts. Solutions for these problems are available and can be applied.

Potential and water-limited yields of present cultivars are slightly underestimated by CGMS which calls for a calibration using recent field experiments. Other potential improvements of CGMS relate to model processes (e.g., vernalization and re-allocation of assimilates) and input data, such as the use of winter and spring wheat land use maps, refinement of the estimation of initial soil water content and initial biomass and the use of a better data source for radiation.

CGMS uses local weather, soil and crop data with a complete spatial coverage (top down) to simulate (spatial variability) of yields over Europe which makes it an interesting benchmark for the proposed bottom-up approach in the global yield gap atlas project (www.yieldgap.org).

Acknowledgements

The crop monitoring and crop yield forecasting work by Alterra, Wageningen University and Research, has been commissioned by the Joint Research Centre of the European Commission at Ispra, Italy (http://ies.jrc.ec.europa.eu/). Among other activities this work supports the operation and maintenance of the CGMS system. For more information about recent developments of the MCYFS, see http://mars.jrc.ec.europa.eu/mars.

FADN data for 1990–2006 have been supplied by the European Commission (see http://ec.europa.eu/agriculture/rica/) for the SEAMLESS project and its continuation, the SEAMLESS Association.

Wheat yield data from variety trials have been kindly supplied by Bert Rijk, Plant Production Systems Group, Wageningen University (see http://www.kennisakker.nl/kenniscentrum/document/rassenbulletin-wintertarwe).

References

Bartholomé, E., Belward, A.S., 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. Int. J. Remote Sens. 26-9, 1959–1977.
Baruth, B., Royer, A., Klisch, A., Genovese, G., 2008. The use of remote sensing within the MARS crop yield monitoring system of the European Commission. In: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XXXVII, Part B8, Beijing.
Baruth, B., Genovese, G., Montanarella, L., 2006. New Soil Information for the MARS Crop Yield Forecasting System. European Communities, Luxembourg, ISBN 92-79-03376-X.
Beek, E.G., Stein, A., Jansen, L.L.F., 1992. Spatial variability and interpolation of daily precipitation amount. Stoch. Hydrol. Hydraul. 6, 304–320.
Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Change Biol. 13, 679–706.
Boogaard, H.L., Van Diepen, C.A., Rötter, R.P., Cabrera, J.M.C.A., Van Laar, H.H., 1998. User's guide for the WOFOST 7.1 crop growth simulation model and WOFOST control center 1.5. Technical Document 52. Winand Staring Centre, Wageningen, the Netherlands, 144 pp.
Boons-Prins, E.R., De Koning, G.H.J., Van Diepen, C.A., Penning de Vries, F.W.T., 1993. Crop specific simulation parameters for yield forecasting across the European Community. In: Simulation Reports CABO-TT No. 32, CABO-DLO, Wageningen, the Netherlands, 43 pp. + Appendices.
Bouman, B.A.M., Van Keulen, H., Van Laar, H.H., Rabbinge, R., 1996. The 'School of de Wit' crop growth simulation models: pedigree and historical overview. Agric. Syst. 52, 171–198.
CBS, Statline, 2012. See http://statline.cbs.nl/statweb/?LA=en
De Koning, G.H.J., Van Diepen, C.A., 1992. Crop production potential of rural areas within the European Communities. IV. Potential, water-limited and actual crop production. In: Working Document W68, Netherlands Scientific Council for Government Policy, the Hague, The Netherlands.
Deryng, D., Sacks, W.J., Barford, C.C., Ramankutty, N., 2011. Simulating the effects of climate and agricultural management practices on global crop yield. Glob. Biogeochem. Cycl. 25, 1–18.
Eitzinger, J., Thaler, S., Schmid, E., Strauss, F., Ferrise, R., Moriondo, M., Bindi, M., Palosuo, T., Rötter, R., Kersebaum, K.C., Olesen, J.E., Patil, R.H., Saylan, L., Çaldağ, B., Çaylak, O., 2012. Sensitivities of crop models to extreme weather conditions during flowering period demonstrated for maize and winter wheat in Austria. J. Agric. Sci., 1–23.
EUROSTAT, 2005. European Regional and Urban Statistics—Reference Guide. European Communities.
Fischer, R.A., Edmeades, G.O., 2010. Breeding and cereal yield progress. Crop Sci. 50, 85–98.
Fischer, G., Van Velthuizen, H., Shah, M., Nachtergaele, F.O., 2002. Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results. IIASA RR-02-02, IIASA, Laxeburg, Austria.
Genovese, G., Bettio, M. (Eds.), 2004. Methodology of the MARS Crop Yield Forecasting System. Statistical Data Collection, Processing and Analysis, vol. 4. European Communities, Luxembourg, ISBN 92-894-8183-8.
Godfray, H.C.J., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Nisbett, N., Pretty, J., Robinson, S., Toulmin, C., Whiteley, R., 2010. The future of the global food system. Philos. Trans. R. Soc. B 365, 2769–2777.
Gozzini, B., Crisci, A., Bertini, D., Maselli, F., Meneguzzo, F., Zipoli, G., Paniagua, S., Perarnaud, V., Van Diepen, C.A., Boogaard, H.L., Courault, D., Delecolle, R.,2000. Cooperation and comparison of several interpolation methods of meteorological data (minimum temperature). In: COST Action 79. European Communities (EUR 19545), Luxembourg.
Groot, J.J.R., Verberne, E.L.J., 1991. Response of wheat to nitrogen fertilization, a data set to validate simulation models for nitrogen dynamics in crop and soil. Nutr. Cycl. Agroecosyst. 27, 349–383.
Hengsdijk, H., Meijerink, G.W., Mosugu, M.E., 2005. Modeling the effect of three soil and water conservation practices in Tigray, Ethiopia. Agric. Ecosyst. Environ. 105, 29–40.
Hough, M.N., 1990. Agrometeorological Aspects of Crops in the United Kingdom and Ireland. A Review for Sugar Beet, Oilseed Rape, Peas, Wheat, Barley, Oats, Potatoes, Apples and Pears. European Communities (13039 EN).
Janssen, S., Andersen, E., Athanasiadis, I.N., Van Ittersum, M.K., 2009. A database for integrated assessment of European agricultural systems. Environ. Sci. Policy 12, 573–587.
Kemanian, A.R., Stöckle, C.O., Huggins, D.R., Viega, L.M., 2007. A simple method to estimate harvest index in grain crops. Field Crop. Res. 103, 208–216.
Lazar, C., Genovese, G. (Eds.), 2004. Methodology of the MARS Crop Yield Forecasting System. Agrometeorological Data Collection, Processing and Analysis, vol. 2. European Communities, Luxembourg, ISBN 92-894-8181-1.
Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., Ramankutty, N., 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? Glob. Ecol. Biogeogr. 19, 769–782.

Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007. GEPIC-modelling wheat yield and crop water productivity with high resolution on a global scale. Agric. Syst. 94, 478–493.

MMA, 2007. El agua en la economia Espanola: situation y perspectivas, working document. Madrid.

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

Micale, F., Genovese, G., 2004. Methodology of the MARS Crop Yield Forecasting System. Meteorological Data Collection, Processing and Analysis, vol. 1. European Communities (EUR 21291 EN), Luxembourg.

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet. 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob. Biogeochem. Cycl. 22, 1–19.

Narciso, G., Ragni, P., Venturi, A., 1992. Agrometeorological Aspects of Crops in Italy, Spain and Greece. A Summary Review for Common and Durum Wheat, Barley, Maize, Rice, Sugar Beet, Sunflower, Soya Bean, Rape, Potato, Cotton, Olive and Grape Crops. European Communities (EUR 14124 EN), Luxembourg.

Nelson, G.C., Rosegrant, M.W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., 2010. Food Security, Farming, and Climate Change to 2050. IFPRI, Washington, DC.

Neumann, K., Verburg, P.H., Stehfest, E., Muller, C., 2010. The yield gap of global grain production: spatial analysis. Agric. Syst. 103, 316–326.

Palosuo, T., Kersebaum, K.C., Angulo, C., et al., 2011. Simulation of winter wheat yield and its variability in different climates of Europe: a comparison of eight crop growth models. Eur. J. Agron. 35, 103–114.

Parry, M.L., Rosenzweig, C., Iglesias, A., Fischer, G., Livermore, M., 1999. Climate change and world food security: a new assessment. Glob. Environ. Change 9, 51–67.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob. Environ. Change 14, 53–67.

Penning De Vries, F.W.T., Rabbinge, R., Groot, J.J.R., 1997. Potential and attainable food production and food security in different regions. Philos. Trans. R. Soc. B: Biol. Sci. 352, 917–928.

Rappoldt, C., Boogaard, H.L., Brodský, L., Kodešová, R., Van Diepen, C.A., 2012. Extension of the WOFOST soil water submodel. Comparison with SWAP and technical documentation. Project report commissioned by the Joint Research Centre, Ispra, Italy.

Rabbinge, R., Van Diepen, C.A., 2000. Changes in agriculture and land use in Europe. Eur. J. Agron. 13, 85–99.

Reidsma, P., Ewert, F., Boogaard, H.L., Van Diepen, C.A., 2009. Regional crop modelling in Europe. The impact of climatic conditions and farm characteristics on maize yields. Agric. Syst. 100, 51–60.

Roerink, G.J., Bojanowski, J., De Wit, A.J.W., Eerens, H., Supit, I., Leo, O., Boogaard, H.L., 2012. Evaluation of MSG-derived global radiation estimates for application in a regional crop model. Agric. Forest Meteorol. 160, 36–47.

Rötter, R., Palosuo, T., Kersebaum, K.C., Angulo, C., Bindi, M., Ewert, F., Ferrise, R., Hlavinka, P., Moriondo, M., Nendel, C., Olesen, J.E., Patil, R.H., Ruget, F., Takáč, J., Trnka, M., 2012. Simulation of spring barley yield in different climatic zones of Northern and Central Europe: a comparison of nine crop models. Field Crops Res. 133, 23–36.

Rötter, R., Van Keulen, H., Jansen, M.J.W., 1997. Variations in yield response to fertilizer application in the tropics. I. Quantifying risks and opportunities for smallholders based on crop growth simulation. Agric. Syst. 53, 41–68.

Rötter, R., Van Keulen, H., 1997. Variations in yield response to fertilizer application in the tropics. II. Risks and opportunities for smallholders cultivating maize on Kenya's arable land. Agric. Syst. 53, 69–95.

Russell, G., Wilson, G.W., 1994. An Agro-Pedo-Climatological Knowledge Base of Wheat in Europe. European Communities (EUR 15789 EN), Luxembourg.

Savin, I.Y., Ovechkin, S.V., Aleksandrova, E.V., 1997. The WOFOST simulation model of crop growth and its application for the analysis of land resources. Eurasian Soil Sci. 30, 758–765.

Siebert, S., Döll, P., Feick, S., Hoogeveen, J., Frenken, K., 2007. Global Map of Irrigation Areas Version 4.0.1. Johann Wolfgang Goethe University, Frankfurt am Main, Germany/Food and Agriculture Organization of the United Nations, Rome, Italy.

Slewinski, T.L., 2012. Non-structural carbohydrate partitioning in grass stems: a target to increase yield stability, stress tolerance, and biofuel production. J. Exp. Bot. 63, 4647–4670.

Stehfest, E., Heistermann, M., Priess, J.A., Ojima, D.S., Alcamo, J., 2007. Simulation of global crop production with the ecosystem model DayCent. Ecol. Model. 209, 203–219.

Supit, I., Van Diepen, C.A., De Wit, A.J.W., Wolf, J., Kabat, P., Baruth, B., Ludwig, F., 2012. Assessing climate change effects on European crop yields using the Crop Growth Monitoring System and a weather generator. Agric. Forest Meteorol. 164, 96–111.

Supit, I., Van Diepen, C.A., De Wit, A.J.W., Kabat, P., Baruth, B., Ludwig, F., 2010. Recent changes in the climatic yield potential of various crops in Europe. Agric. Syst. 103, 683–694.

Supit, I., Wagner, W., 1998. Analysis of yield, sowing and flowering dates of barley of field survey results in Spain. Agric. Syst. 59, 107–122.

Supit, I., Van Kappel, R.R., 1998. A simple method to estimate global radiation. Sol. Energy 63, 147–160.

Supit, I., Hooijer, A.A., Van Diepen, C.A. (Eds.), 1994. System Description of the WOFOST 6.0 Crop Simulation Model Implemented in CGMS. European Communities (EUR15956EN), Luxembourg.

Trigo, I.F., Dacamara, C.C., Viterbo, P., Roujean, J.L., Olesen, F., Barroso, C., Camacho-De-Coca, F., Carrer, D., Freitas, S.C., García-Haroj, J., Geiger, B., Gellens-Meulenberghs, F., Ghilain, N., Meliá, J., Pessanha, L., Siljamo, N., Arboleda, A., 2011. The satellite application facility for land surface analysis. Int. J. Remote Sens. 32, 2725–2744.

Van der Voet, P., Van Diepen, C.A., Oude Voshaar, J., 1993. Spatial interpolation of daily meteorological data: a knowledge based procedure for the regions of the European Communities. Report 53/3. The Winand Staring Centre, Wageningen, and the Joint Research Centre, Ispra, Italy.

Van Diepen, C.A., Wolf, J., Van Keulen, H., Rappoldt, C., 1989. WOFOST: a simulation model of crop production. Soil Use Manage. 5, 16–24.

Van Diepen, C.A., De Koning, G.H.J., 1990. Crop Data Files for Use with WOFOST Version 5.0.

Van Heemst, H.D.J.,1988. Plant data values required for simple crop growth simulation models: review and bibliography. In: Simulation Report CABO-TT 17. Centre for Agrobiological Research (CABO) and Department of Theoretical Production Ecology, Agricultural University Wageningen, The Netherlands.

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., Leffelaar, P.A., Van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. Eur. J. Agron. 18, 201–234.

Willekens, A., van Orshoven, J., Feyen, J., 1998. Estimation of the Phenological Calendar, Kc-curve and Temperature Sums for Cereals, Sugar Beet, Potato, Sunflower and Rape Seed across Pan Europe, Turkey and the Maghreb Countries by Means of Transfer Procedures, vol. 1. Project Report. Joint Research Centre of the European Communities. Space Applications Institute, MARS, Project, Ispra, Italy.

Wolf, J., Hessel, R., Boogaard, H.L., De Wit, A., Akkermans, W., Van Diepen, C.A., 2011. Modeling winter wheat production over 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. Advances in Agricultural Systems Modeling 2: Trans-disciplinary Research, Synthesis, and Applications. ASA-SSSA-CSSA Book Series, pp. 297–326.

Wolf, J., Van Diepen, C.A., 1995. Effects of climate change on grain maize yield potential in the European Community. Clim. Change 29, 299–331.

Wolf, J., 1993. Effects of climate change on wheat production potential in the European Community. Eur. J. Agron. 2, 281–292.

Wu, D., Yu, Q., Lu, C., Hengsdijk, H., 2006. Quantifying production potentials of winter wheat in the North China Plain. Eur. J. Agron. 24, 226–235.