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A model for crop yield and water footprint assessment: Study of maize in the Po valley

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ABSTRACT

We tested here a simple, hydrologically based, multi-year daily crop model called *PolyCrop* (*PC*), and tested it for the purpose of reproducing the dynamics of maize (*Zea Mais L.*) within two case study areas in the Po valley of Italy, namely Persico Dosimo (Cremona province), and Livraga (Lodi province), and to subsequently calculate water use therein, in the form of *water footprint* indicators. The model uses daily information of weather drivers given by temperature, precipitation, and solar radiation to simulate soil water budget, crop growth and crop yield, providing daily estimates of soil moisture, evapotranspiration, leaf area index *LAI*, and biomass. We simulated maize growth in Persico Dosimo using the *PC*, and the reference model from the literature *Cropsyst* (*CS*), and we validated our simulations against crop productivity data during 2001–2010. We then simulated maize growth in Livraga for 3 years (2010–2012), and we compared (i) actual evapotranspiration, and soil moisture against daily field measurements taken by an eddy covariance tower, and TDR probes, (ii) biomass against results from simulations with *CS*, and (iii) *LAI* against estimates from MODIS satellite images at 1 km resolution with eight-day frequency of acquisition. We then calculated *water footprint* (green water footprint, WF_G, and blue water footprint, WF_B) of maize in the area, defined as the absolute and specific (per kg yield) amount of water evapotranspired during the growing season, and we use *PC* and *CS* models to assess WF_G, and WF_B, under the present irrigation scheme. We benchmarked our WF estimates against available estimates in the reference literature. The *PC* model performs comparably well in depicting daily dynamics of maize growth, soil moisture, and *LAI*, and *water footprint* of the crop system, and therefore we are confident that it may be useful for crop growth simulation, as necessary to tackle a number of issues, including *e.g.* (i) assessment of crop productivity under current climate and management, (ii) short to medium term forecast of yield and soil moisture for a sustainable irrigation management, (iii) assessment of water usage of cropping systems, and (iv) modified crop and water footprint conditions under prospective climate change, using climate forcing from GCMs and other climate models. Future developments may regard inclusion of nutrient dynamics, which is not a limiting factor nowadays for growth in the Po valley, but may concern use of or crop model elsewhere, or here in the future.

1. Introduction

Agriculture is heavily impacted by present climate change, and potential reduction of harvest may lead to larger water requirements for sustainable yield (Torriani et al., 2007; Bocchiola et al., 2013), and decline of *food security* worldwide (Adams et al., 1998; Olesen and Bindi, 2002; Olesen et al., 2007; Schmidhuber and Tubiello, 2007; Tubiello et al., 2007; Strzepek and Boehlert, 2010; Supit et al., 2010). Agriculture is a highly water consuming activity (Rost et al., 2008; Fader et al., 2011), and water resources worldwide are heavily exploited for food production (Konar et al., 2011). This trend is increasing under population growth pressure (Strzepek and Boehlert, 2010), and recently increased agricultural land deals that led to transnational water abstraction (Rulli et al., 2013) to sustain food requirements. The concept of *virtual water* was introduced (Allan, 1993), *i.e.* the water embodied in the production and trade of agricultural commodities, and assessment of *virtual water trade* between nations is now a mean to quantify worldwide budget of water resources (Hoekstra and Hung, 2005). A key concept to virtual water quantification is the *water footprint* (WF, Hoekstra (2003a,b)), developed for water use assessment in the production of goods, especially food (Aldaya and Hoekstra, 2010). *Water footprint* and *virtual water trade* are

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used to assess implications of worldwide trading strategies for *food security*, also pending climate warming (*e.g.* Rosenzweig and Hillel, 1998; Easterling and Apps, 2005; Ferrero, 2006; FAO, 2009). Most relevant crops worldwide are cereals, especially wheat *Triticum* L., maize *Zea Mais L.*, and rice *Oryza* L., requiring significant amount of water for production, *i.e.* rainfall and irrigation during Summer (Tubiello et al., 2000; Torriani et al., 2007; Bocchi and Castrignanò, 2007; Confalonieri et al., 2009, 2011; Fava et al., 2010; Rossi et al., 2010). This in turn implies considerable *water footprint*, and *virtual water trade* when crops are sold or bought (Bocchiola et al., 2013). Under transient climate change conditions like we are experiencing now, modified (increased, *e.g.* Torriani et al., 2007) use of water by crops (per unit of yield) may cascade into modified (increased?) *water footprint*, requiring adaptation strategies. Adaptation requires the understanding of crop systems dynamics and water consumption, and of the linkage to climate drivers, most notably (increase of) temperature and (lack of) precipitation (*e.g.* Bocchiola et al., 2013).

Modeling tools, including crop models, are necessary because they mimic crop production from agricultural sites under specific climate conditions (*e.g.* Richter et al., 2010), and can be later used to assess potential effect of climate variations (*e.g.* Soussana et al., 2010). Along with crop yield, crop models may provide water requirements, leaf area index *LAI*, soil moisture, evapotranspiration, that are usable for a number of conjectures. Before crop models are used confidently their outputs need to be validated against independently gathered measurements, or estimates of (some of) the output variables (*e.g.* Confalonieri and Bechini, 2004; Confalonieri et al., 2009). Methods for validation may include field measurements of productivity (Donatelli et al., 1997), *LAI* (Stroppiana et al., 2006), soil moisture (Confalonieri and Bechini, 2004), or estimation of these variables using remote sensing (Bocchi and Castrignanò, 2007).

Here we tested a simple, hydrologically based, spatially distributed multi-year daily crop model, which we called *PolyCrop* (henceforth, *PC*). *PC* is based upon the inclusion of a relatively simple crop growth module within a semi-distributed (*i.e.* upon a cells' grid) hydrological model (Groppelli et al., 2011; Bocchiola et al., 2013). The purpose of *PC* model development was to allow assessment of the hydrological cycle, crop growth, and water use within a disparate array of topographic and environmental conditions, ranging from low altitude and desert areas, to mountain areas, with large environmental gradients, and cryospheric areas, including seasonal snow cover, and permanent ice, and also areas with permafrost. The *PC* model was tested successfully, among others, in the desert environment and climate of Sardinia region of Italy (pasture, Addimando et al., submitted for publication), the low altitude continental areas of the Po valley of Italy (maize, Nana et al., 2013, and rice, Merletti, 2014), the Alpine area of Italy (Retiche Alps, high altitude pastures above 2000 masl, Addimando, 2013), and the cold desert areas of Karakoram (Pakistan, 2000 to 3000 masl, pastures, Addimando, 2013).

The purpose of this paper was to demonstrate the potential of *PC* by carrying out a multi-parameter validation of its performance in simulating the dynamics of maize within two sites in the case study area of Po valley, in Lombardia region of Italy, and in subsequently calculating *water footprint* indicators. We wanted to demonstrate that (i) *PC* provides an accurate depiction of the hydrological budget in cropping systems, (ii) *PC* mimics accurately crop yield, and (iii) *PC* can be used to acceptably depict *water footprint* of cropping.

First, we studied maize growth within a case study area in the town of Persico Dosimo (in Cremona province, see *e.g.* Bocchiola et al., 2013), where we possessed data of maize yield (ton ha^{-1}, dry) lumped on Cremona province, by the Italian institute of statistics (ISTAT) for 2001–2010. We then simulated maize growth in Livraga, Lodi province, where personnel from Politecnico di Milano has carried out lately intensive experiments concerning hydrological fluxes, and soil moisture budget (Corbari et al., 2012; Masseroni et al., 2012) during 2010–2012.

We compared *PC* output of (i) actual evapotranspiration, against field measurements by an eddy covariance tower, (ii) soil moisture, against data from TDR probes, (iii) leaf area index (*LAI*), against MODIS satellite images of *LAI* at 1 km resolution, and (iv) crop yield data from literature and farmers' indication. To further benchmark our results we used the well-known model *Cropsyst* (henceforth, *CS*, Bellocchi et al., 2002; Confalonieri and Bechini, 2004; Confalonieri et al., 2009). We evaluated the observed *water footprint* (green water footprint, WF_G, and blue water footprint, WF_B) of maize in the area, in the form of absolute (mm), specific (per kg yield), and relative (per mm rainfall) amount of water evapotranspired during the growing season, and we used *PC* and *CS* models to assess WF_G, and WF_B. We compared our WF estimates against those from some recent studies, to benchmark our results, and to highlight the importance of site specific assessment of water use in agriculture.

2. Materials and methods

2.1. Study areas

Lombardia region is nested within the Po valley of Northern Italy, among the most productive agricultural landscapes in Europe, with farming areas covering 45% of the catchment. Major crops are wheat, maize, barley *Hordeum vulgare L.*, sugar beets *Beta vulgaris L.*, and rice. According to Eurostat (2012) Lombardia region had an average (1999–2007) cereals production of 8.83 ton ha^{-1}, comparable with the most productive areas in Europe, such as the East Flanders in Belgium (9.56 ton ha^{-1}), the Alsace in France (9.19 ton ha^{-1}), the Noord-Bradant in Holland (9.09 ton ha^{-1}), and the Schleswig–Holstein in Germany (8.37 ton ha^{-1}). Water management in the Po valley is dependent upon an intricate system of reservoirs, lakes and authorities, providing operation under a multi-objective perspective (Galelli et al., 2010). Tackling assessment of crop yield, and water use in this area is therefore utmost important. Cremona and Lodi provinces (Fig. 1) are laid within the southern, most arid end of Lombardia region, covering 1771 km^2, and 780 km^2, respectively, with altitude between 20 and 100 masl. Almost 81% of the territory is used for agricultural production. Cremona, and Lodi province belongs to an area with continental/warm climate (Köppen-Geiger climate classification, *e.g.* Peel et al., 2007) with average year round temperatures of +12–14 °C and average rainfall 650–900 mm. Winter is cold (+2.5 °C on average) and Summer is hot (+23 °C on average). The air is typically moist, fog is frequent and wind speed is low. Rainfall regime is bimodal, with a higher maxima in Fall, and a lower one in early Spring. Soil substrates in the area are made of coarse silty loam deposits down to about half meter, below which is finer silty loam to about 1 m. Soil is generally well drained and has relatively low permeability. The water table is about 1.5 m under the surface, and there are two aquifers, parted by an *acquitard*, with an average transmissivity, roughly between 4×10^{-3} m s^{-1} and 1.5×10^{-2} m s^{-1}. The study area in Cremona province surrounds the town of Persico Dosimo (Fig. 1), featuring ca. 3000 inhabitants, laid at 48 m above sea level (masl), and covering ca. 20 km^2 northwest of Cremona. Irrigation strategies of local farmers were gathered via interviews, suggesting that maize fields are normally watered five times during growth season, starting at the end of May, about every 20 days with an average amount of 50 mm each time (250 mm in all on average). Livraga (Fig. 1) is laid within Lodi province, in southern end of the Lombardia region, covering 782 km^2, with altitude between 60 and 100 masl. The case study field of

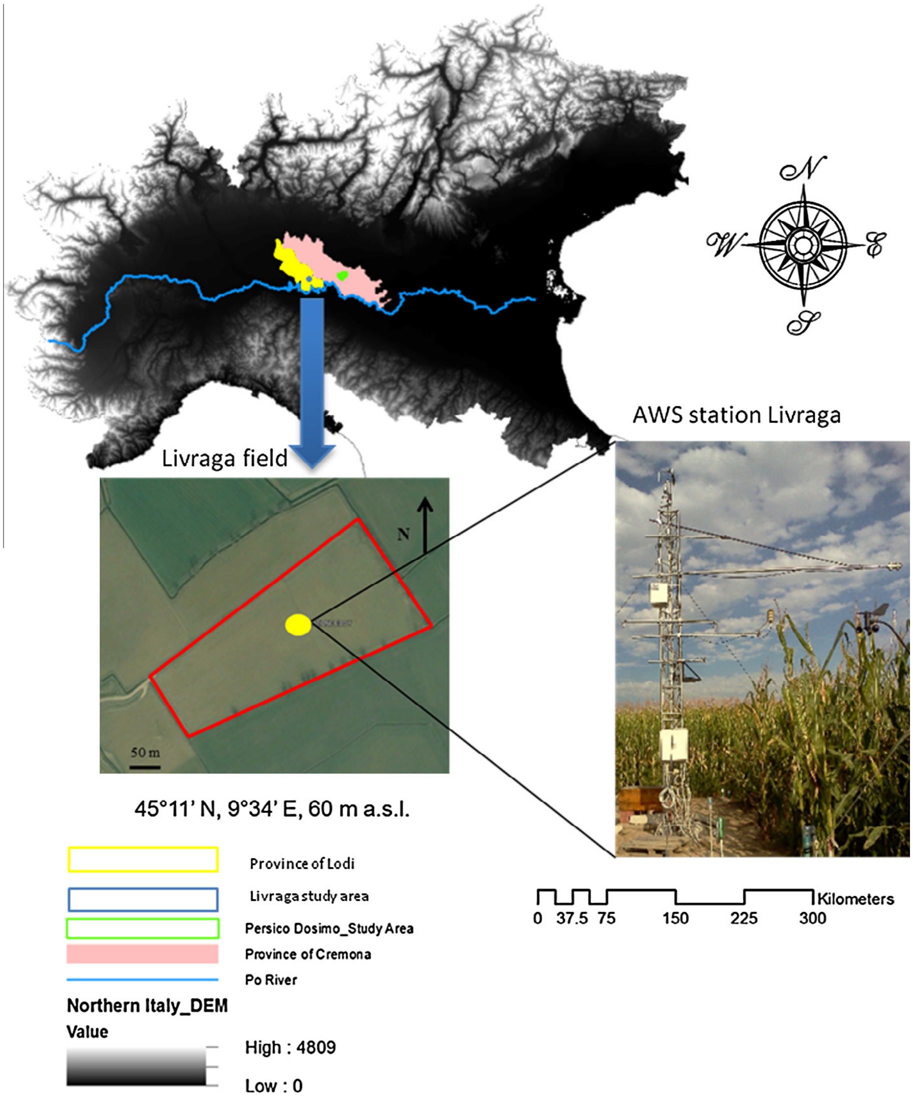

Fig. 1. Case study areas. Livraga field site and AWS station of Politecnico di Milano are displayed.

Livraga (45°11′ N, 9°34′ E, 60 masl), in the Province of Lodi, has an area of 10 ha, surrounded by other maize fields. Experimental measurements were carried out during 2010–2012, mostly in the vegetative season, *i.e.* since May 25th to September 10th in 2010, since May 9th to August 20th in 2011, since and May 21st to September 7th in 2012. The study parcel is within the irrigation consortium, *Consorzio Muzza*, with more than 70 km of open canals for irrigation. The study field is irrigated by flooding, and several irrigation runs are performed every year. According to farmers, each irrigation run was is quantified in around 100 mm. Particularly, in 2010 three irrigation runs were performed, upon June 14th, and July 7th and 31st, during 2011 only two runs were performed, upon June 29th and July 22nd, in 2012 three runs were performed, on June 29th, July 14th and August 5th.

2.2. Data base

In the town of Persico Dosimo an automatic weather station is available, property of the regional environment protection agency ARPA (Agenzia Regionale Protezione dell'Ambiente). However, we verified a considerable lack of data in the data base. We decided to use the data base provided by the European Community under the project Crop Growth Monitoring System (CGMS), developed by Monitoring Agricultural ResourceS (MARS) unit of Joint Research Centre (JRC). The CGMS data base is optimally suited for agricultural simulation (Confalonieri et al., 2009). We used here the meteorological data provided in the CGMS project at the grid point $\varphi = 45°12'$ and $\lambda = 10°12'$, the closest to Persico Dosimo ($\varphi = 45°11'$, $\lambda = 10°6'$). Comparison against ARPA data showed good agreement. Average (2001–2010) yearly rainfall was $P_{av} = 914$ mm.

In Livraga, a number of data were acquired by way of an AWS station located in the maize field, operated by Politecnico of Milano (Corbari et al., 2012; Masseroni et al., 2012). The station measured the principal mass and energy fluxes, such as net radiation, evapotranspiration and soil moisture. A 3D sonic anemometer (Young 81000), and a gas analyzer (LICOR 7500) measured air moisture at 5 m above ground, working at 20 Hz frequency. A rain gage (AGR100 by Campbell Scientific) measured rainfall, two thermocouples (by ELSI), and a heat flux plate (HFP01 by Hukseflux) measured the specific energy flux leaving the ground surface. The four components of the net radiation were measured by a CNR1 Kipp and Zonen radiometer, at 4 m above ground, while soil moisture was measured by CS616 Campbell Scientific probes at different depths, from 10 cm to 65 cm, based upon Time Domain Reflectometry TDR. Data were stored each 30 min. Energy fluxes were processed by applying a number of correction procedures (Lee et al., 2004; Foken, 2008). A number of instrumental and physical corrections were automatically implemented in the Polimi Eddy Covariance (*PEC*) software, developed by Corbari et al. (2012). During the vegetation season, crop height was constantly measured in the field manually. The satellite images of *LAI* used for model validation were acquired from MODIS radiometers on board of TERRA and AQUA NASA satellites (MOD15A2 8-day composite *LAI/FPAR* product, http://ladsweb.nascom.nasa.gov, Myneni et al., 2002). *LAI* maps were retrieved in the form of composite images upon an 8-days period, with a spatial resolution of 1 km. A composition period of 8 days is a good compromise between the need to avoid cloudy conditions, and the need to describe *LAI* dynamics, reasonably well captured with such sampling frequency (Claverie et al., 2013).

2.3. PolyCrop model

We used the spatially semi-distributed *PC* model (Addimando, 2013; Nana et al., 2013), obtained by nesting a crop growth module into a spatially distributed hydrological model already developed and used at Politecnico di Milano (Groppelli et al., 2011; Bocchiola et al., 2013). The vegetation growth module is developed with the aim of providing a simplified version of a crop growth model, such as *Cropsyst* model (Stöckle et al., 2003). The hydrological model, through a water budget scheme, provides soil water content, used by the vegetation module to simulate crop growth. In turn, the crop growth module provides daily values of *LAI*, used by the hydrological model to calculate the transpiration and fraction of vegetated soil, and modified soil water content through water use of crop. Both modules work at a daily scale upon a grid cells scheme, with size defined by the user. Each cell has its own topography, vegetation, meteorological inputs variables and soil properties. At present, lateral flows are neglected, valid for large cells, and flat areas, with little lateral redistribution, as in our case study areas. Only one soil layer was considered for simplicity. The hydrological model is based upon a simplified daily step water budget equation

$$S^{t+\Delta t} = S^{t} + P + I - ET - Q_g - Q_s, \tag{1}$$

where S is soil water content, P is rainfall, I is irrigation, ET is (actual) evapotranspiration, Q_g is groundwater discharge, and Q_s is overland superficial flow, all expressed in consistent units [mm]. The crop growth model estimates daily biomass as the minimum value between a water (transpiration) dependent growth (G_{TR}), and a solar radiation dependent growth (G_R).

$$G_{TR} = \frac{T_{eff} BTR}{VPD}; \quad G_R = LtBc \cdot PAR \cdot f_{PAR} \cdot T_{lim}, \tag{2}$$

with G_{TR} [kg m^{-2} day^{-1}] transpiration dependent biomass growth, T_{eff} [m day^{-1}] effective (actual) transpiration, VPD [kPa] average vapor pressure deficit, BTR [kPa kg m^{-3}] biomass transpiration coefficient, G_R [kg m^{-2} day^{-1}] radiation dependent biomass growth, L_{tbc} [kg MJ^{-1}] light to biomass conversion coefficient, PAR [MJ m^{-2} day^{-1}] photosyntetically active radiation, f_{PAR} [·] fraction of incident PAR intercepted by canopy, and T_{lim} temperature limitation factor [·]. We assumed full availability of soil nutrients, so nitrogen budget did not need to be simulated here (*i.e.* N is not a limiting factor). Such assumption is not generally true, but a preliminary investigation indicated that manuring with nitrogen in our case study area provides full availability of nutrients. Crop growth stages are based upon accumulation of thermal time (or degree days) during the growth season (Stöckle and Nelson, 1999). In the presence of vegetation biomass, the evapotranspiration depends on the *LAI*, which is iteratively calculated for each day of the simulation. The effective transpiration depends upon the daily vegetation growth, and its vegetative stage (Stöckle et al., 1994), as

$$f_{PAR} = 1 - \exp(-kLAI_{cum}), \tag{3}$$

and

$$T_{eff} = 86400 \frac{c}{1.5} (\psi_s - \psi_x), \tag{4}$$

where k [·] is the extinction coefficient for solar radiation, LAI_{cum} [m^2 m^{-2}] is leaf area index as cumulated until the day when f_{PAR} is calculated, C [kg s m^{-4}] is the root conductance, Ψ_s is soil water potential [J kg^{-1}], Ψ_x [J kg^{-1}] is leaf water potential, 86,400 is number of seconds per day, and 1.5 is a factor converting root conductance into hydraulic conductance. Here, the *PC* model is used in a point-wise (*i.e.* not distributed) manner, given the limited size of the investigated area. However, as reported, it can be operated at a spatially distributed scale (*e.g.* Addimando, 2013; Addimando et al., submitted for publication).

2.4. Model setup

The model requires series of daily precipitation, maximum and minimum temperature, and solar radiation, available from different sources. Information about soil properties and use was made available by the regional agency for agriculture and forest services ERSAF (Ente Regionale per i Servizi all'Agricoltura e alle Foreste) for both sites. Main soil properties are given in Table 1. Further information about maize is necessary for both *Poly-Crop*, and *CropSyst* set up. Some of these parameters were taken from former studies (Donatelli et al., 1997) and are reported in Table 2. Some parameters are site-specific, and it was necessary to carry out a calibration phase of the most sensitive parameters against yield data (Table 3), by tuning within their documented range of variability, as provided by the *CropSyst* user manual (Stöckle and Nelson, 1999). Both *CropSyst* and *Poly-Crop* models allow use of different irrigation strategies for plant growth simulation, namely (i) no irrigation (NO), (ii) automatic irrigation (AU), *i.e.* on demand, and (iii) manual irrigation (MA), according to farmers' strategies. Here, we tried and use MA option (*i.e.* as done by farmers here) by taking the values reported in Section 2.1 to validate the models against observed data.

2.5. Water footprint

We calculated water consumption for cropping adopting the concept of green and blue *water footprint* by Hoekstra (2003a,b) and Hoekstra and Chapagain (2008), already used in several studies (Rost et al., 2008; Fader et al., 2011). This is a numerical index (either dimensional, *e.g.* mm, or specific, *e.g.* kg kg^{-1}), expressing the amount and origin of water used for the production of a given good. In agreement with Rost et al. (2008) we used (i) green *water footprint* ($\mathrm{WF_G}$), and (ii) blue *water footprint* ($\mathrm{WF_B}$). Green *water footprint* is the consumption of water stored in the ground as a result of precipitation. We evaluated $\mathrm{WF_G}$ by comparing evapotranspiration during the growth season (ET_g), as simulated by the two models, against the cumulative precipitation during the growing season (P_g)

$$\begin{aligned} &\text{if} \quad ET_g \geqslant P_g \quad \mathrm{WF_G} = P_g \\ &\text{if} \quad ET_g < P_g \quad \mathrm{WF_G} = ET_g \\ &ET_g = E_{s,g} + T_{c,g}, \end{aligned} \tag{5}$$

where $E_{s,g}$ is soil evaporation and $T_{c,g}$ is transpiration from the crop during the growing season. When actual evapotranspiration during the growth season exceeded precipitation, the latter was entirely used, either productively for plant growth, or unproductively for

Table 1
Soil properties as required by *CropSyst* (*CS*), and *PolyCrop* (*PC*).

Variable	Persico Dosimo				Livraga		
	CS Layer 1	CS Layer 2	CS Layer 3	CS Layer 4	PC Layer 1	CS Layer 1	PC Layer 1
Depth [m]	0.35	0.25	0.15	0.60	1.6	1.0	1.0
Sand [%]	13.20	15.80	11.90	11.20	12	14	14
Silt [%]	65.30	62.00	67.10	60.80	65	60	60
Clay [%]	21.50	22.20	21.00	28.00	23	26	26

Table 2
Agricultural parameters. *CropSyst* (*CS*), and *PolyCrop* (*PC*).

Growth parameters	Persico		Livraga	
	CS	PC	CS	PC
Biomass/transpiration coefficient [kPa kg m^{-3}]	7.60	7.60	8.5	8.5
Conversion light/biomass [g MJ^{-1}]	4.00	4.00	4.00	4.00
Real/potential transpiration, end of leaf growth [·]	0.50	0.50	0.50	0.50
Real/potential transpiration, end of root growth [·]	0.50	–	0.5	–
Mean daily temperature optimal growth, T_{opt} [°C]	18.00	18.00	16	16
Max daily water consumption, W_{maxd} [mm d^{-1}]	12.00	12.00	10	10
Hydr. leaf potential, onset stomatal closure [J kg^{-1}]	−1200	−1200	−1200	−1200
Hydraulic potential, leaf wilting [J kg^{-1}]	−1800	−1800	−1800	−1800
Morphology				
Max root depth, d_{Rmax} [m]	1.20	1.20	0.8	0.8
Initial green area index [m^2 m^{-2}]	0.011	0.011	0.005	0.005
Max leaf area index, LAI_{max} [m^2 m^{-2}]	5.00	–	5.00	–
Fraction LAI_{max} at maturity [·]	1.00	–	1.00	–
Specific leaf area *SLA* [m^2 kg^{-1}]	25.00	25.00	19.00	19.00
Partition stem/leaf [m^2 kg^{-1}]	2.80	2.80	2.80	2.80
Leaf duration [°C d]	750	750	890	890
Extinction coefficient of solar radiation [·]	0.45	0.45	0.55	0.55
Sensitivity of leaf to water stress (0–3) [·]	1.00	–	1.00	–
Evapotranspiration coefficient K_c [·]	1.19	1.19	1.19	1.19
Phenology				
Degree-day emergence [°C d]	52.00	52.00	80	80
Degree-day LAI peak [°C d]	870.00	–	900	–
Degree-day flowering [°C d]	920.00	920	950	950
Degree-day at *grain filling* [°C d]	1050.00	–	1100	–
Degree-day maturity [°C d]	1650.00	1650.00	1650	1650
Base temperature [°C]	8.00	8.00	8.00	8.00
Threshold temperature [°C]	30.00	30.00	30.00	30.00
Phenologic sensitivity water stress (0–3) [·]	1.00	–	1.00	–
Harvest				
Harvest index, no stress [·]	0.52	0.52	0.52	0.52
Sensitivity water stress flowering [·]	0.40	–	0.40	–
Sensitivity water stress flowering *grain filling* [·]	0.40	–	0.40	–
Translocation factor [·]	0.40	–	0.40	–

Table 3
Calibration parameters for *PolyCrop*, and *Cropsyst*.

Parameters	Range	Persico	Livraga
Growth reduction threshold [°C]	0–25	18	16
Specific leaf area [m^2 kg^{-1}]	15–25	25	19
Partition stem/leaf [·]	1–10	2.80	2.80
Leaf duration [°C d]	700–1000	750	890
Degree-day emergence [°C d]	0–300	52	80
Degree-day flowering [°C d]	300–1500	920	950
Degree-day maturity [°C d]	1000–2500	1650	1650
Threshold temperature [°C]	0–10	10	10
Cutoff temperature [°C]	20–30	30	30
Biomass/transpiration coefficient [kPa kg m^{-3}]	3–9	7.6	8.5

soil evaporation. Conversely, when P_g was higher than ET_g, WF_G was estimated via the latter, *i.e.* in case of abundant precipitation, evapotranspiration was entirely sustained by precipitation. Water from rainfall infiltrates into soil, and modifies water content θ. If enough rainfall occurs, enough soil moisture is available and ET_g is entirely fulfilled. We neglected the potential effect of water losses due to runoff via Q_s or Q_g, in periods of wet soil. Preliminary simulations demonstrated that both Q_s and Q_g were always small in comparison with the amount of precipitation and irrigation. For instance, in Livraga cumulated $P + I$ during the growth season of 2010–2012 was of 1480 mm (680 P, 800 I), and $Q_s + Q_g$ reached no more than 87 mm, more or less equally distributed. Both occurred significantly during irrigation events. We found similar results for Persico Dosimo. Therefore, rainfall water was entirely used for evapotranspiration, substantiating use of Eq. (5). This occurs here in view of the low precipitation amounts, and large evapotranspiration, keeping soil moisture quite low. We also neglected water present in crop biomass, which is however small against ET_g.

Blue *water footprint* refers to the consumption of blue water resources, *i.e.* water flowing into rivers and lakes, or extracted from underground, and not directly deriving from precipitation during the cropping season (Rost et al., 2008; Fader et al., 2011). The consumption in this case makes reference to the loss of water available from superficial or underground water bodies. We evaluated $\mathrm{WF_B}$ as

$$\begin{array}{lll} \text{if} & ET_g \geqslant P_g & \mathrm{WF_B} = ET_g - P_g \\ \text{if} & ET_g < P_g & \mathrm{WF_B} = 0, \end{array} \tag{6}$$

i.e. the actual evapotranspiration not accounted for by precipitation is the blue *water footprint*, coming from either irrigation, or soil storage. Eq. (6) is used to avoid including the runoff part generated by irrigation into the blue water footprint, because runoff water is not used for evapotranspiration by the crop. Again, runoff was on average low as compared against the input of $P + I$, so this issue is practically irrelevant in our case study.

We used also *specific* (green or blue) *water footprint* (WF^*) as the amount of water in kg necessary to produce 1 kg of harvested yield Y, namely

$$\mathrm{WF}^*_{\mathrm{G,B}} = \frac{\mathrm{WF_{G,B}}}{Y}, \tag{7}$$

together with *relative* (green or blue) *water footprint* $\mathrm{WF^P}$, *i.e.* the ratio of *water footprint* to P_g

$$\mathrm{WF^P_{G,B}} = \frac{\mathrm{WF_{G,B}}}{P_g}. \tag{8}$$

We neglected the gray *water footprint* (Mekonnen and Hoekstra, 2011), *i.e.* the water volume required to dilute pollutants, such as fertilizers. Calculation of gray *water footprint* requires simulation of the mass budget of fertilizers (here nitrogen), and possibly validation against samples of incoming and outgoing concentration of nutrients into water, not carried out here as reported.

3. Results

3.1. Model validation

In Persico Dosimo, we carried out several test runs of *PC* and *CS*, to obtain yield data coherent with those given by ISTAT (partially reported in Bocchiola et al., 2013, for *CS* model). In the absence of biomass data in Livraga, we used as a control variable soil water content (−35 cm, where most complete series were available). In Table 3, calibration parameters for the two models are displayed. In Persico Dosimo, we continuously simulated soil water balance and crop growth during the growth season with *PC* and *CS*, from January 1st 2001 to December 31st 2010, to keep into account water storage dynamics for the whole period. In Livraga, we simulated with *PC* and *CS* the period from January 1st 2010 to December 31st 2012. In Figs. 2 and 3 we report the best simulations in the tuning phase, in term of productivity (dry crop biomass), against ISTAT productivity (in Persico D.), and average value as reported by farmers (Livraga). In Persico Dosimo, simulation using Manual irrigation MA (watering five times during growth season, with 50 mm each time) provided acceptable agreement, except for 2006, when both *CS*, and *PC* simulated lower yields than the ISTAT data (see Bocchiola et al., 2013, reporting about *CS* simulations in Persico D.), as given by water stress during the growing season. Thus, the 250 mm of water applied in 2006 based upon farmer interviews was not enough to sustain maize growth. We used therefore automatic irrigation AU, which provided a yield closer to the ISTAT one during 2006. AU option better interprets the likely behavior of farmers, who in the presence of a drier than usual season would feed the crop field more water than usual, which probably happened during 2006. Therefore, and given that the approximate irrigation scheduling may not be representative of the real behavior of farmers in the area, we decided to use AU mode for calculations. Indeed, use of either MA or AU mode would not change much productivity, and its variability, and water usage in Persico Dosimo simulation (see also Bocchiola et al., 2013), so the results for the two modes are not largely different. In Figs. 4–6 we report for Livraga site, *CS* and *PC* performance against observed data of leaf area index *LAI*, actual evapotranspiration *ET*, and soil moisture θ, respectively. We report (Table 4) the models' validation statistics against biomass (Persico D., and Livraga, only average), and *LAI*, *ET*, θ (Livraga). Namely, we report random mean square error, absolute (*RMSE*), and in percentage ($RMSE_{\%}$), mean error absolute (*Bias*), and percentage ($Bias_{\%}$). Here, given that irrigation schedule was provided specifically (and soil moisture was available), we could use MA irrigation mode with acceptable results.

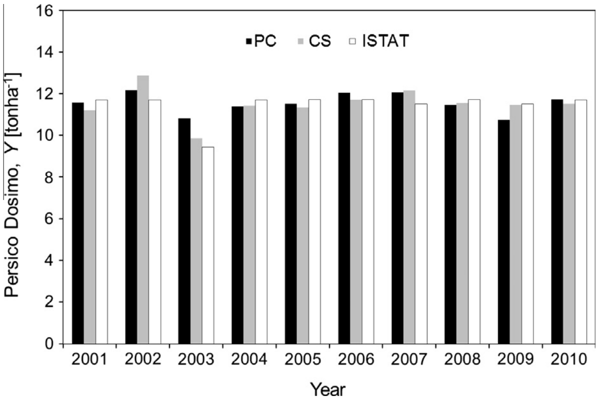

Fig. 2. Persico Dosimo. *Cropsyst* and *PolyCrop* yield validation against ISTAT data, period 2001–2010.

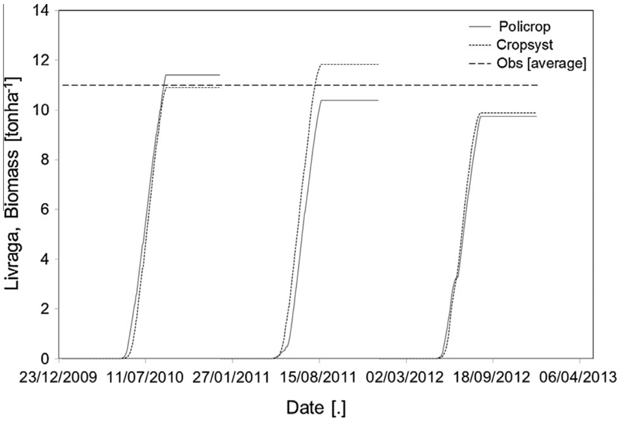

Fig. 3. Livraga. *Cropsyst* and *PolyCrop* biomass yield during 2010–2012, compared against average estimated biomass during 2010–2012 according to local farmers.

3.2. Water footprint

Water footprint calculated by Eqs. (5) and (6) is reported (Figs. 7a and 8a). WF is given for both *PC* and *CS*, together with its value from observed *ET* (for Livraga, Fig. 8). The latter displayed some missing data (*ET* in Fig. 5), so we carried out linear interpolation. In Figs. 7b and 8b we report specific and relative WF, $\mathrm{WF}^*_{\mathrm{G,B}}$, and $\mathrm{WF^P}$ ($\mathrm{WF^P_G}$ given by 100% threshold of $\mathrm{WF^P}$ in Fig. 7b and a, the exceedance being $\mathrm{WF^P_B}$) in Eqs. (7) and (8), from *PC*, *CS*, and observed *ET* (only in Livraga), and P_g data. Actual crop yield was not available in Livraga, so we used the average value of *PC* and *CS* to calculate $\mathrm{WF}^*_{\mathrm{G,B}}$ for comparative purposes.

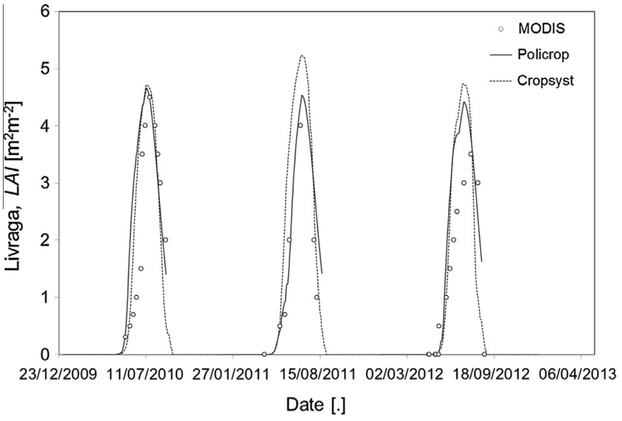

Fig. 4. Livraga. *Cropsyst* and *PolyCrop* estimation of *LAI* during 2010–2012 against estimates from MODIS.

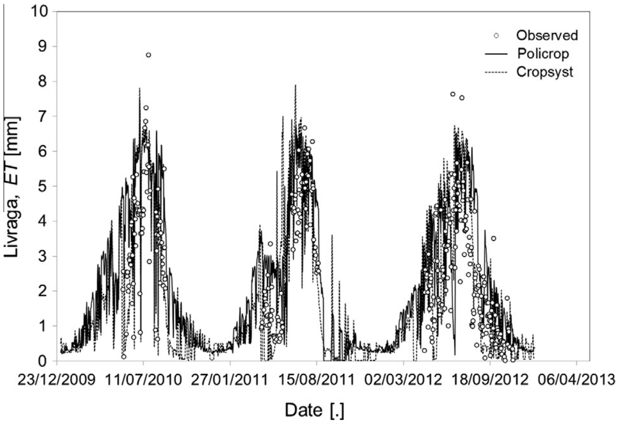

Fig. 5. Livraga. *Cropsyst* and *PolyCrop* estimation of actual evapotranspiration during 2010–2012 against estimates from Eddy Correlation station.

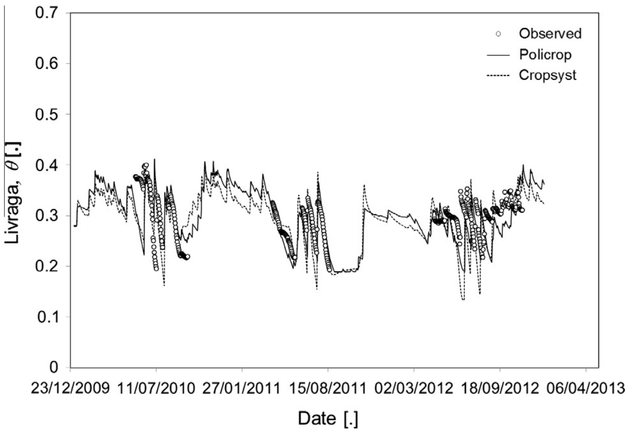

Fig. 6. Livraga. *Cropsyst* and *PolyCrop* estimation of soil moisture during 2010–2012 against estimates from TDR probes (−35 cm).

Table 4
Validation statistics, mean values, absolute and percentage bias *Bias* and *Bias*$_{\%}$, and absolute and percentage random mean square error *RSME*, *RSME*$_{\%}$. Observed biomass in Livraga given as average (2010–2012) value by farmers, in *Italic*. *CropSyst* (*CS*), and *PolyCrop* (*PC*).

Persico Dosimo		*Y* [ton ha^{-1}]	E[*Y*]	11.43
PC E[*Y*]	PC Bias	PC Bias%	PC RMSE	PC RMSE%
11.55	+0.12	+1.04	0.58	5.68
CS E[*Y*]	CS Bias	CS Bias%	CS RMSE	CS RMSE%
11.51	+0.08	+0.69	0.51	4.43
Livraga Source/Var	*Y* [ton ha^{-1}]	*LAI* [m^2 m^{-2}]	*ET* [mm d^{-1}]	θ [·]
Obs	*11*	1.69	3.4	0.294
PC mean	10.51	1.22	4.2	0.296
PC Bias	−0.49	−0.47	0.8	0.002
PC Bias%	−4	−28	+23	0.9
PC RMSE	–	1.03	1.89	0.05
PC RMSE%	–	61.3	67.2	17.1
CS mean	10.87	1.77	3.7	0.279
CS Bias	−0.13	−0.45	0.3	−0.015
CS Bias%	−1	−27	+9	−5.1
CS RMSE	–	1.07	1.87	0.06
CS RMSE%	–	63.7	66.3	19.4

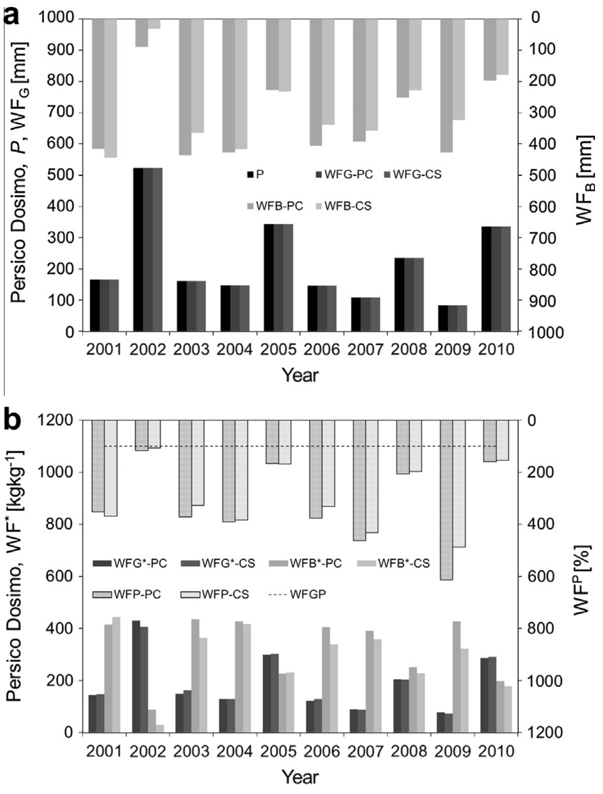

Fig. 7. Persico Dosimo. *Cropsyst* and *PolyCrop* evaluation of WF during 2001–2010. (a) Absolute WF$_G$, WF$_B$, against rainfall during growth season P. (b) Specific WF$^*_G$, WF$^*_B$, and relative WF^P. Hundred percent value of WF^P indicates full use rainfall (WF^P_G part), with the exceedance being blue part WF^P_B.

4. Discussion

The *PC* model, simpler than other state of the art crop models (*e.g. CS*), reproduced acceptably well some features of our cropping systems. In Persico Dosimo *PC* performed comparably well against *CS*, and provided acceptable biomass estimates. The systematic error in biomass estimation was small (+12% *vs CS* +8%), and *RMSE* was acceptable (0.58 ton ha^{-1}, *CS* 0.51 ton ha^{-1}). Inaccuracies (*RMSE*$_{\%}$) nearby 20% or so are commonly accepted in crop growth simulation (*e.g.* Cho et al., 2007), and our model was able to perform within this range. The variability of the yearly Crop yield (coefficient of variation, CV) was reasonably well reproduced, (*PC*, 0.05, *CS*, 0.06, Obs, 0.06), important when assessing crop yield

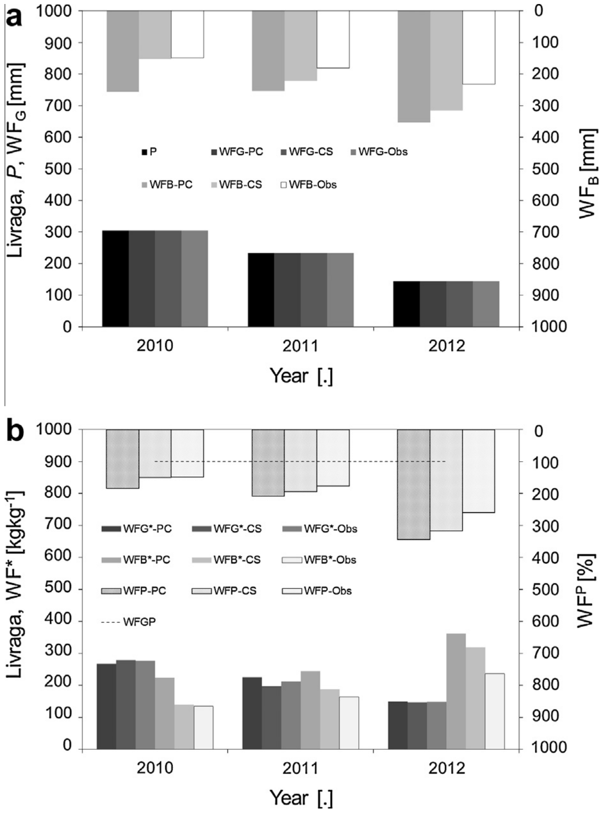

Fig. 8. Livraga. *Cropsyst* and *PolyCrop* evaluation of WF during 2010–2012. Also the observed counterparts (*i.e.* using actual *ET* and average crop yield *Y* as reported by farmers) are reported. (a) Absolute $\mathrm{WF_G}$, $\mathrm{WF_B}$, against rainfall during growth season *P*. (b) Specific $\mathrm{WF^*_G}$, $\mathrm{WF^*_B}$, and relative $\mathrm{WF^P}$. Hundred percent value of $\mathrm{WF^P}$ indicates full use rainfall ($\mathrm{WF^P_G}$ part), with the exceedance being blue part $\mathrm{WF^P_B}$.

variability from each other year, for *food security* assessment under (changing?) climate conditions (Torriani et al., 2007). Calculation of water footprint (Fig. 7a) displayed some differences between *PC*, and *CS*. While $\mathrm{WF_G}$ was substantially the same, *i.e.* seasonal precipitation P_g was entirely used, $\mathrm{WF_B}$ was higher for *PC* than for *CS* ($\mathrm{E[WF_{B,PC}]}$ = 327 mm, *vs* $\mathrm{E[WF_{B,CS}]}$ = 291 mm, *i.e.* +12% for *PC*). The simulated evapotranspiration was slightly higher for *PC* ($\mathrm{E}[ET_{PC}]$ = 551 mm, *vs* $\mathrm{E}[ET_{CS}]$ = 516 mm), *i.e.* with *PC* displaying +7% *ET* than *CS*. This subsequently increased the estimates of $\mathrm{WF^*}$ (Fig. 7b). While again $\mathrm{WF^*_G}$ was essentially the same ($\mathrm{E[WF^*_{G,PC}]} = \mathrm{E[WF^*_{G,CS}]} = 194\ \mathrm{kg\ kg^{-1}}$), $\mathrm{WF^*_B}$ was slightly different ($\mathrm{E[WF^*_{B,PC}]} = 285\ \mathrm{kg\ kg^1}$, $\mathrm{E[WF^*_{B,CS}]} = 258\ \mathrm{kg\ kg^{-1}}$, or +10% for *PC*). Relative $\mathrm{WF^P}$ was also higher for *PC* ($\mathrm{E[WF^P_{,PC}]}$ = 3.21 $\mathrm{mmmm^{-1}}$, -$\mathrm{E[WF^*_{B,CS}]} = 2.95\ \mathrm{kg\ kg^{-1}}$, or +9% for *PC*). Actual *ET* was unknown to us in Persico Dosimo, and there is no telling whether models' estimates were accurate, and which model performed better.

In Livraga case study, biomass data (Fig. 3) were not available, unless as an estimate of average value, respected by both models ($Bias_{\%}$, −4% for *PC*, −1% for *CS*). The comparison against the satellite derived *LAI* (Fig. 4) displayed a range of variation fully comparable with those derived from MODIS data. Average error was similar for both models, and acceptable ($Bias_{\%}$, −28% for *PC*, −27% for *CS*), also considering potential noise within *LAI* estimates from MODIS. Noise $RMSE_{\%}$ was also similar ($RMSE_{\%}$, 61% for *PC*, 64% for *CS*). Comparison of *LAI* date wise may provide some noise, due to date mismatch given by use of 8-days composites of MODIS. However, analysis of Fig. 4 indicates that the dynamics of *LAI* was acceptably depicted by the models, and *PC* captured *LAI* at peak slightly better than *CS*. In Fig. 5 we reported simulated *vs* observed *ET* in Livraga. Visually, both models depicted reasonably well *ET* patterns. The bias in *ET* estimation was larger for *PC* than for *CS* ($Bias_{\%}$, +23% for *PC*, +9% for *CS*, and *PC* delivers +13% *ET* than *CS*), and the difference was similar to what found in Persico Dosimo above. Model noise was comparable ($RMSE_{\%}$, 67% for *PC*, 66% for *CS*). Given the inherent variability of measuring and modeling *ET*, these results seem encouraging. Visual analysis of Fig. 6 indicates that both the crop models were able to mimic soil moisture θ. *PC* displayed slightly better performance ($Bias_{\%}$, +0.9% for *PC*, −5% for *CS*, $RMSE_{\%}$, 17% for *PC*, 19% for *CS*).

The slight overestimation displayed by both *CS*, and (more evidently) by *PC* against observed *ET* values will require finer tuning (and prosecution of local measurements) in the future. However, given the uncertainty entailed into *ET* fluxes calculation using sophisticate techniques such as Eddy Correlation (here PEC, Corbari et al., 2012; Masseroni et al., 2012), the level of agreement we found seems preliminarily acceptable. In the future, also remotely sensed *ET* fluxes may be used for model's validation (*e.g.* Corbari et al., 2013), explicitly allowing assessment of outputs from our *PC* spatially distributed model.

As a benchmark, we took recent studies of crop models' validation against observed crop variables. An overview of *CS* performance against observed yield was provided by Stöckle et al. (2003). Therein, a number (5) of studies were reported, where *Bias*, and *RMSE* in calculation of different crops (Maize, 2 cases, Wheat, Sorghum, Soybean, one case each) were evaluated. Yield therein varied roughly between 2.8 ton $\mathrm{ha^{-1}}$ (Soybean) and 19 ton $\mathrm{ha^{-1}}$ (Maize), and *Bias* (absolute value) roughly between 25 $\mathrm{kgha^{-1}}$ (Soybean, $Bias_{\%}$ 0.9%), and −0.68 ton $\mathrm{ha^{-1}}$ (Maize, $Bias_{\%}$ 4%), consistent with our findings here. $RMSE_{\%}$ ($RMSE/\mathrm{E}[Y]$) ranged between 7% (Sorghum), and 21% (Maize), again fairly consistent with our results. Confalonieri et al. (2009) validated *WARM*, *Cropsyst* and *WOFOST* models for paddy rice (*Oryza sativa L.*) growth modeling in 7 sites of the Po valley. Their *RMSE* varied between 0.68 $\mathrm{tha^{-1}}$ and 2.54 ton $\mathrm{ha^{-1}}$, against an average yield from 10 to 17 ton $\mathrm{ha^{-1}}$. Confalonieri and Bechini (2004) used *CS* model to assess yield of pasturelands (Alfalfa, *Medicago sativa L.*) in two meadows nearby Lodi. They measured a cumulative yield (3 years) of 38.2 and 36.9 ton $\mathrm{ha^{-1}}$, with 14 cuts. *RMSE* for *Y* ranged between 3% and 6% for calibration, and between 3% and 5% for validation. *RMSE* for θ ranged between 13% and 21% for calibration, and between 10% and 20% for validation, against 17–19% here. Ouda et al. (2010) tuned *CS* to predict Barley (*Hordeum vulgare L.*) yield in Egypt. Considering 6 different sites (2 years field campaign), they obtained $Bias_{\%}$ within +1.43%. *RMSE* was nearby 0.04 ton $\mathrm{ha^{-1}}$, *i.e. ca.* 1%, particularly low.

Our *LAI* estimates were acceptable when compared to MODIS product MOD15A2. Satellited derived *LAI* may entail some inaccuracy, given the complex algorithms required to manipulate reflectances (Knyazikhin et al., 1998a,b), and the spatial scale of estimation. Suàrez Urrutia (2010) tested *LAI* from MODIS-15 product against ground data of rice yield in Seville, Spain, gathered in Summer 2008. They found that *LAI* from MOD15A2 would underestimate (by 50% or so) observed (weekly averaged) measured rice *LAI*. Fensholt et al. (2004) validated MODIS (daily, averaged upon 16 days windows) *LAI* products using *in situ* measured *LAI* from three sites in Senegal (2001–2002). They found that MOD15A2 *LAI* was overestimated by approximately +2–15%.

Tian et al. (2002) used field measured *LAI* in four 200 × 300 transects in Botswana in March 2000 to validate *LAI* from MODIS at 250 m, 500 m, and 1000 m resolution, showing that MODIS algorithm tends to underestimate *LAI* (about −5% from 1 $\mathrm{km^2}$ MODIS data), the magnitude depending upon the vegetation type, spatial, and pixel heterogeneity. Claverie et al. (2013) studied accuracy of MOD15A3 *LAI* products (4-days period, 1 $\mathrm{km^2}$ resolution) in 7 seven crop fields (3 with maize) near Toulouse, France. Comparing MOD15A3 data against reference maps, they found $Bias_{\%}$ = −8%, and $RMSE_{\%}$ = 23%. Our results, highlighting slight overestimation of the modeled *LAI* (Fig. 4) may also suffer from inaccuracy of the latter. Evapotranspiration was slightly overestimated by *CS* and (more) by *PC*. Evapotranspiration covers a large share of the hydrological budget in our region (*e.g.* Groppelli et al., 2011), is largely variable and seldom measured, and no validation against measured *ET* of cropping models exists that we know of, so our results here seemingly provide an interesting benchmark.

Water footprint in Fig. 8a and b provides room for discussion. Again, WF_G was similar for the two models, given that rainfall was entirely used for crop growth. WF_B was overestimated by both models ($E[WF_{B,PC}] = 287$ mm, *vs* $E[WF_{B,CS}] = 230$ mm, $E[WF_{B,Obs}] = 180$ mm, *i.e.* +59% for *PC*, and +27% for *CS*). WF^*_G was essentially the same for both models ($E[WF^*_{G,PC}] = 214\ \text{kg kg}^{-1}$, $E[WF^*_{G,CS}] = 208\ \text{kg kg}^{-1}$, $E[WF^*_{G,Obs}] = 212\ \text{kg kg}^{-1}$), while WF^*_B was different ($E[WF^*_{B,PC}] = 277\ \text{kg kg}^{-1}$, $E[WF^*_{B,CS}] = 215\ \text{kg kg}^{-1}$, $E[WF^*_{B,Obs}] = 179\ \text{kg kg}^{-1}$). Relative WF^P was also higher for *PC* ($E[WF^P_{,PC}] = 2.4$, $E[WF^P_{B,CS}] = 2.2$, $E[WF^P_{B,Obs}] = 2.0$). Notice that i) observed *ET* series had some missing data (ca. 25%), and ii) we did not have available actual (yearly) biomass, both circumstances possibly impacting our results here.

Our findings indicate that one needs on average ca. 450–480 kg kg^{-1} (*CS*, *PC*) in Persico D., and 380, 420, 490 kg kg^{-1} (*Obs* with some missing data of *ET* and only approximate yield, *CS*, *PC*) in Livraga, with a 28% variability. The ratio of total water used to seasonal rainfall gives values of 2.9 to 3.2 (*CS*, *PC*) in Persico D., and 2.0, 2.2, 2.4 (*Obs*, *CS*, *PC*) in Livraga, somewhat smaller.

WF is often used for conjectures about water consumptions, and virtual water trade at worldwide scale (Rost et al., 2008; Fader et al., 2011; Konar et al., 2011) based upon broad scale calculations, and reference values for different crops are available in the present literature.

As a benchmark for water footprint of maize, Barthélemy et al. (1993), reported in Zimmer and Renault, 2003) quantified specific (total) water consumption of maize crop as $WF^* = 710\ \text{kg kg}^{-1}$, referring to arid climate of California, Egypt, Tunisia. Hoekstra (2003a,b) reported estimates of *virtual water* embedded in maize, *i.e.* water footprint, ranging from 450 kg kg^{-1} on average worldwide, as given by Hoekstra and Hung (2003), to 1900 kg kg^{-1} referred to Japan, as given by Oki et al. (2003). Clearly, water footprint of maize (as of any other cereal) is largely variable, depending upon country and climate (see Table 2 in Mekonnen and Hoekstra, 2010a), and a proper assessment needs to be done within each specific area. Mekonnen and Hoekstra (2010a), based upon FAOSTAT data and results from Mekonnen and Hoekstra (2010b), who estimated crop water footprint at a 5 by 5 arc minute spatial resolution globally, provided specific water consumption, green and blue, for maize in several countries worldwide (1996–2005), including Italy. Mekonnen and Hoekstra (2010a) reported for Lombardia region on average $WF^*_G = 410\ \text{kg kg}^{-1}$, $WF^*_B = 91\ \text{kg kg}^{-1}$, or a total $WF^* = 501\ \text{kg kg}^{-1}$. The *PC* model provided on average $WF^*_G = 214\ \text{kg kg}^{-1}$ and $WF^*_B = 277\ \text{kg kg}^{-1}$, *i.e.* $WF^* = 491\ \text{kg kg}^{-1}$ in Livraga, and $WF^*_G = 193\ \text{kg kg}^{-1}$, and $WF^*_B = 285\ \text{kg kg}^{-1}$, *i.e.* $WF^* = 478\ \text{kg kg}^{-1}$ in Persico Dosimo, with similar values from *CS*, and measurements in Livraga. Our estimates of specific water footprint WF^* match properly those by Mekonnen and Hoekstra (2010a), while our WF^*_G is higher than theirs. In our target area, precipitation during growth season was on average of 225 mm during 2001–2010 in Persico Dosimo, and 228 mm during 2010–2012 in Livraga. Given the average crop productivity of 11.5 ton ha^{-1} in Persico Dosimo, and of 11 ton ha^{-1} in Livraga, WF^*_G cannot exceed on average the values reported above nearby 200 kg kg^{-1}, and WF^*_B was consequently higher. While the coincidence of our estimated total water footprint against that by Mekonnen and Hoekstra (2010a) confirms the validity of *PC* to evaluate water use for maize cropping, the accurate distinction between green and blue water footprint is tightly linked to local climate (and especially precipitation), and requires investigation on a site to site basis, while spatially averaged values as those provided by Mekonnen and Hoekstra (2010a) upon a large spatial grid may not be representative enough. Accordingly, our *PC* model is a valuable tool for site specific WF computation.

The *PC* model makes a number of simplifying assumptions with respect to *CS*, including use of one single soil layer, and depiction of soil properties, and of crop phenology using fewer parameters than *CS*, (Tables 1 and 2). Full availability of nutritive substances in the soil is hypothesized, which is not granted, albeit likely not relevant in our target area here. Future developments of the model should therefore include nutrients' dynamics. With the caveats as discussed above, our *PC* model seems to perform comparably well in depicting maize growth, and *water footprint* in our case study area, and it may be usable in the future for tackling a number of issues, including *e.g.* (i) assessment of crop productivity under current climate and management, (ii) short to medium term forecast of yield and soil moisture for a sustainable irrigation management, (iii) assessment of water usage of cropping systems, and (iv) modified crop and water footprint conditions under prospective climate change, using climate forcing from GCMs and other climate models (*e.g.* as preliminarily explored by Nana et al., 2013).

Po valley is a most productive agricultural area in Europe, and proper crop management under climate change impact must be tackled soon enough. Recent studies have demonstrated that transient climate change within the next half century will likely lead to decreased Summer flows from rivers in the Italian Alps (Anghileri et al., 2011; Groppelli et al., 2011), cascading into enhanced conflicts in the use of water (Soncini et al., 2011). Moreover, evidence is being raised that future WF of maize, and other crops in this area will increase (*e.g.* Bocchiola et al., 2013), so strategies for monitoring, modeling, and decreasing large scale water consumptions are necessary.

5. Conclusions

We presented a new, hydrologically based crop yield model *PC* and tested it in two case study areas with maize. *PC* performed well in our validation experiment against hydrological and crop yield data, also in comparison with the reference *CropSyst*. Crop yield models are often validated against crop indexes, and less against other water related variables, so our results are of interest. We then investigated site specific water footprint. Water footprint is often inferred, say for virtual water trade assessment, using Tables derived from (large scale) estimates based upon few studies, and seldom at site estimation is carried out. Our results are therefore relevant, because they demonstrate that (i) crop models, and particularly our *PC* can be used for credible assessment of yield and water use in cereal cropping, and (ii) water footprint components (green and blue) need to be assessed by way of local investigation under site specific climate conditions.

The *PC* model is nested upon a spatially distributed hydrologically based model, so crop yield and water footprint may be estimated upon areas displaying environmental gradients, changes in the meteorological inputs, variable topography, soil texture, and different irrigation strategies, and within different regions worldwide. Eventually, our results provide a tool usable for (i) distributed crop yield assesment (ii) evaluation of water requirements, and (iii) testing of optimal watering strategies, also under climate change. Accordingly, our work delivers a relevant contribution in the area of water resources management, especially to the ongoing debate about *food security* in Europe and worldwide.

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