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Impact of climate change scenarios on crop yield and water footprint of maize in the Po valley of Italy

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ABSTRACT

We studied the effect of prospective climate change upon crop yield, and related *water footprint* of maize (*Zea mays* L.) for a relevant case study area in the Po valley of Northern Italy. To simulate maize production we used a cropping system simulation model *CropSyst*, which we set up and validated by way of crop yield data during 2001–2010. We then calculated the present *water footprint* (green, blue) of maize in the area, defined as the absolute and specific (per kg yield) amount of water evapotranspired during growing season, under three irrigation scenarios, namely (i) no irrigation, (ii) manual irrigation at fixed dates, and (iii) automatic irrigation on demand. We then evaluated the effects of prospective climate change upon maize production until mid-century (2045–2054), and we quantified the *water footprint* therein. We considered climate variations with focus upon temperature, precipitation, and CO_2. First, we assessed maize yield and *water footprint* sensitivity to potential changes of these weather variables. We then fed the maize yield model with properly downscaled climate projections (storyline A2, *business as usual*) from global circulation models (GCM), included within the board of the Intergovernmental Panel of Climate Change, IPCC, and with those from a local scenario LOC, obtained by projecting recently observed local climate trends (1975–2010). Under the worst, more likely future scenarios of increasing temperature and decreasing precipitation, crop yield decreased and *water footprint*, especially blue, increased, due to increased evapotranspiration, higher irrigation demand, and lower final yield. Increase of CO_2, albeit possibly increasing water use efficiency, seemed not to affect the *water footprint* noticeably. A possible increase of precipitation as projected by some GCMs, may partly make up for the increase of temperature, especially under a no, or little irrigation scenario, further diminishing the blue *water footprint*. Uncertainty in future precipitation has the greatest impact in scenarios projecting maize yield and *water footprint*. Our study provides hints as to how one can (i) evaluate the amount of water required to cultivate maize or other crops, and virtually traded when such crops are sold or bought, (ii) evaluate the impact of climate change upon water footprint and virtual water trade, and (iii) benchmark objectively adaptation strategies for agricultural systems with an eye on least water consumption.

1. Introduction

Agriculture is heavily impacted by climate change, and yield reduction may result in the decline of *food security* worldwide (Adams et al., 1998; Olesen and Bindi, 2002). Weather and climate play a primary role in productivity in this sector, in spite of the considerable advances given by technology and science. Agriculture typically requires considerable amount of water for irrigation, and it is a high water consuming activity (Rost et al., 2008; Fader et al., 2011). Water resources worldwide are heavily exploited for food production (e.g. Konar et al., 2011), and increasingly so under population growth pressure (Strzepek and Boehlert, 2010). More recently, scientists have focused upon the concept of *virtual water* (e.g. Allan, 1993), i.e. the water that is embodied in the production and trade of agricultural commodities, and upon *virtual water trade* between nations, as a mean to quantify worldwide budget of water resources (e.g. Hoekstra and Hung, 2005). A key concept to virtual water quantification is the *water footprint* (WF, e.g. Hoekstra, 2003), recently developed as a paradigm for water use assessment in production of goods, and especially food (Aldaya and Hoekstra, 2010). *Water footprint* and *virtual water trade* concepts are tools usable to evaluate 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 for food security are cereals, and especially wheat, *Triticum* L., maize and rice, *Oryza* L. (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), all requiring significant amounts of water for production, i.e. rainfall and irrigation during

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Summer, in turn implying considerable *water footprint*, and *virtual water trade* when sold or bought. Under transient climate change conditions as 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*, so possibly requiring adaptation strategies. Possible effects of climate upon agriculture may include (i) effect of CO_2 increase upon plant respiration cycle, (ii) effects of temperature and rainfall changes, and (iii) effect of sea level rise and reduction of cultivable lands due to soil salinity increases (e.g. Zanoni and Duce, 2003). Doubling of CO_2 may increase photosynthetic rate from 30% to 100%, pending temperature and water availability (Pearch and Bjorkman, 1983). Species of type C3 metabolic pathway (wheat, rice, soybean, *Glycine max*, etc.) react positively (i.e. with increase of yield) to high CO_2. Type C4 metabolic pathway crops (maize, sorghum, *Sorghum* L., sugar cane, *Saccharum* L., millet, *Panicum miliaceum*, etc.) are photosynthetically more efficient, but less sensitive to changes in CO_2 (e.g. Morrison, 1987, 1999). CO_2 further increases water use efficiency via decreased specific (i.e. to leaf area) transpiration. Doubling CO_2 for C3 and C4 species may result in stomatal closure of about 40%, and a reduction of transpiration between 23% and 46% (Cure and Acock, 1987). Increasing temperatures may result in longer potential growth season, and shorter maturation time (e.g. Brouwer, 1988). A temperature increase of 2–3 °C may increase the growing season at the highest (>60°) and medium latitudes (45–60°), while it may limit the growth season at the lowest latitudes due to water stress. Decreased precipitation, if not compensated for by irrigation, may also lead to water stress. With water easily available in the soil, plants have water enough to meet their potential transpiration. With decreasing soil water content plants have to decrease their transpiration to maintain their own water content constant. When prolonged lack of water (rainfall, irrigation) is met and soil moisture drops below wilting point plants may undergo permanent damage.

Climate change as projected for the 21st century may significantly alter crop production (Rosenzweig and Hillel, 1998; FAO, 2009). Referring to the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000), Parry et al. (2004) estimated that while global production is likely to remain stable for most of the century, regional differences could grow stronger through time, with only developed countries possibly benefiting from climate change. Worldwide the impacts of climate change upon crop yield and food security are significant, with a wide projected range, between 5 million and 200 million additional people at risk of hunger by 2100 (Schmidhuber and Tubiello, 2007). Regional differences in the response of crop productivity to climate change are likely to emerge in Europe. As reported by Olesen and Bindi (2002), climate change is expected to have positive impacts only in the Northern countries, and areas of crop suitability may expand northwards (Olesen et al., 2007). Southern areas, on the other hand, will likely have to face decreased crop yield.

In this study we investigated modified water use for maize production, quantified through *water footprint* indicators, in a case study area in Lombardia region, within the Po valley of Northern Italy, among the most productive agricultural areas within Europe. The farming areas in the Po valley cover 45% of the basin's area. Most of the agricultural land in the Po valley is arable land, drained by artificial ditches, and irrigated during summer. Major crops that are grown there are wheat, maize, fodder, barley, *Hordeum vulgare* L., sugar beets, *Beta vulgaris* L., and rice. According to Eurostat (2012) the Lombardia region had an average cereals production of 8.83 ton ha^{-1} during 1999–2007, 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, which provides operation under a multi-objective perspective, including hydropower, crop water, flood prevention, ecological flows, and tourism (Galelli et al., 2010). Tackling prospective climate change impact upon crop yield, water use and food security in the area is therefore a far reaching matter. We calibrated the crop productivity model *CropSyst* against observed productivity indexes (see Confalonieri et al., 2009, 2011; Richter et al., 2010 for an application of *CropSyst* to some case study crops). We then calculated the present green and blue *water footprint* of maize in the area. Green and blue *water footprint* are defined as the absolute or specific (i.e. per kg yield) amount of water evapotranspired during growing season, coming from rain (green) or irrigation (blue), respectively (Rost et al., 2008). We considered three irrigation scenarios, namely (i) no irrigation, (ii) manual irrigation at fixed dates, and (iii) automatic irrigation, on demand. We then evaluated the effects of prospective climate change upon maize production until the mid-century (2045–2054), and we quantified the water footprint therein. We considered climate variations with a focus upon temperature, precipitation and CO_2. First, we assessed maize yield and water footprint sensitivity to potential changes of these weather variables. We then ran the maize yield model with properly downscaled climate projections (storyline A2, business as usual) from four different Global Circulation Models (GCMs) included within the board of the Intergovernmental Panel of Climate Change, IPCC, and with a local scenario, obtained projecting recently observed climate trends (1975–2010). Based on our findings, we discuss potentially modified *water footprint* under climate change, and suggest a number of ways our results may support crop and water management in the Po valley, with an eye upon water consumption.

2. Materials and methods

2.1. Study area

Cremona province (Fig. 1) is laid within the southern end of the Lombardia region, covering an area of 1.77057 km^2, with altitude between 20 and 100 m asl. It is a flatland, with a number of rivers and artificial channels, the latter used to deliver water for agriculture. Almost 81% of the territory is used for agricultural production. Cremona 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 speeds are low. Rainfall regime is bimodal, with a higher maximum in Fall, and a lower one in early Spring. The study area surrounds the town of Persico Dosimo (Fig. 1), featuring ca. 3000 inhabitants, laid at 48 m asl and covering ca. 20 km^2 northwest of Cremona. Soil substrate (*Haplic Calcisol*, *Siltic*, according to WRB classification, 2006) is made of coarse silty loam deposits down to about 45 cm, below which is finer silty loam to about 120 cm. Soil is generally well drained and has relatively low permeability. The water table is ca. 135 cm under the surface, and there are two aquifers, parted by an *acquitard*, with an average trasmissivity between 4×10^{-3} m s^{-1} and 1.5×10^{-2} m s^{-1}.

2.2. Data inputs

Within the town of Persico Dosimo an automatic weather station is available, property of the regional environment protection agency ARPA (Agenzia Regionale Protezione dell'Ambiente),

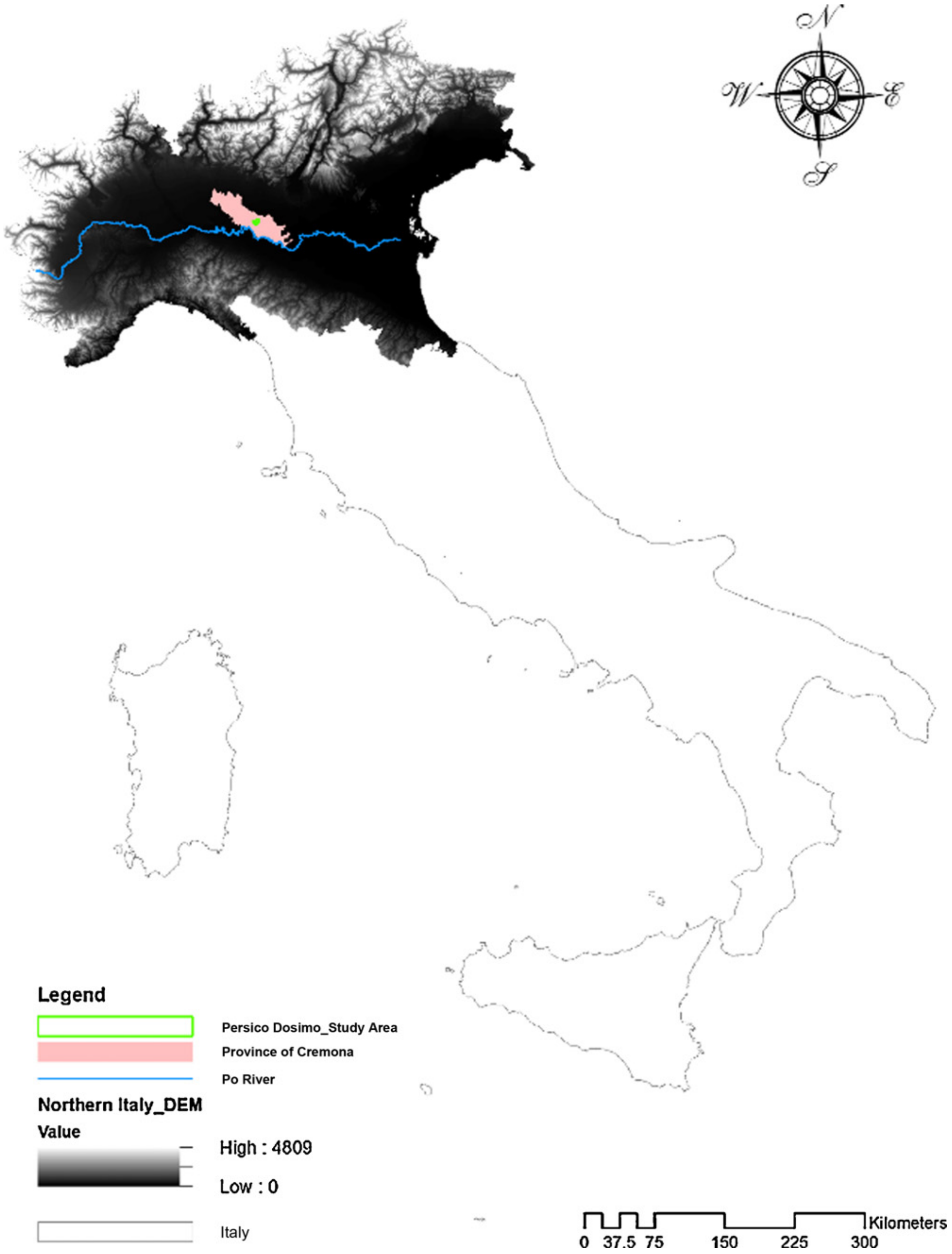

Fig. 1. Case study area.

recording some meteorological data, including those required by *CropSyst* model. The necessary data are namely (i) minimum and maximum daily temperature ($T_{\max}$, $T_{\min}$), (ii) daily precipitation (P), available since 1993, and (iii) daily average solar radiation (R_S), available since 2001. However, we verified a considerable lack of data within the database of ARPA station, making use of these data undependable. We decided therefore to use the database provided by the European Community under the umbrella of the project Crop Growth Monitoring System (CGMS), developed by Monitoring Agricultural ResourceS (MARS) unit of Joint Research Centre (JRC). The CGMS aim is to predict quantitatively the evolution of the agricultural production at a regional scale, and the database delivered within the framework are optimally suited for agricultural simulation (Confalonieri et al., 2009). We used the meteorological data provided in the CGMS project at the grid point $\varphi = 45^\circ 12'$ and $\lambda = 10^\circ 12'$, the closest to Persico Dosimo ($\varphi = 45^\circ 11'$, $\lambda = 10^\circ 6'$). These data were compared against the ARPA data whenever available, showing good agreement. Average yearly rainfall (P_{av}) according to MARS database during 2001–2010 was $P_{av} = 778.30$ mm.

Information about soil properties and use was obtained through the database of the regional agency for agriculture and forest services ERSAF (Ente Regionale per i Servizi all'Agricoltura e alle Foreste) for Persico Dosimo. Main soil properties are given in Table 1.

Further information about cropping species is necessary for *CropSyst* model set up. Some of these parameters were taken from former studies (Donatelli et al., 1997), and are reported in Table 2. The maximum root depth was set for 160 cm for maize, but the model simulates growth as depending upon water availability and soil depth. *CropSyst* explicitly modifies the crop evapotranspiration coefficient (K_c) during the growing season depending upon

Table 1
Soil properties.

Layer	Layer 1	Layer 2	Layer 3	Layer 4
Depth (m)	0.35	0.25	0.15	0.60
Sand (%)	13.20	15.80	11.90	11.20
Silt (%)	65.30	62.00	67.10	60.80
Clay (%)	21.50	22.20	21.00	28.00
pH (.)[a]	6.80	–	–	–
Organic carbon content (%)[b]	2.73	2.50	1.45	1.89
Cationic exchange capacity (meq 0.01 g^{-1})[a]	22.73	–	–	–
Initial water content (m^3 m^{-3})[b]	0.28	0.26	0.23	0.21
Initial nitrate content (NO_3) (kgN ha^{-1})[b]	6.40	24.80	2.60	4.24
Initial ammonium content (NH_4) (kgN ha^{-1})[b]	2.80	10.20	4.80	7.20

[a] Values required only in layer 1.
[b] Values required as inputs by *CropSyst*.

development of leaf area index (*LAI*), and we report here its average value. In turn, *LAI* is calculated in *CropSyst* depending upon biomass increase. In Table 2 we report maximum *LAI* for maize (LAI_{max}).

2.3. Model calibration

Some parameters are site-specific, and therefore it was necessary to carry out a site specific calibration of *CropSyst*, by tuning the most sensitive parameters against observed yield data. We modified the tuning parameters within their documented range of variability, as provided by the *CropSyst* user manual (Stöckle and Nelson, 1999). We used specific (i.e. to surface) yield data (dry weight, ton ha^{-1}), aggregated for the Cremona province, as provided by the Italian institute of statistics (ISTAT) for 2001–2010, while no information was available before 2001. No specific data were available for Persico Dosimo, so we proposed that the province wide specific yield would be representative of local data. Irrigation strategies of local farmers were gathered via interviews, which suggested 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). The *CropSyst* model allows use of different irrigation strategies for plant growth simulation, namely (i) no irrigation (NO), (ii) automatic irrigation (AU), i.e. with allocation of a proper amount of water, and (iii) manual irrigation (MA), according to farmers' strategies. Here, we considered all these three options, to illustrate the impact of irrigation upon the final yield, also under climate change.

Table 2
Agricultural parameters of *CropSyst*.

Growth parameters	Val.
Biomass/transpiration coefficient (kPa kg m^{-3})	7.60
Conversion light/biomass (g MJ^{-1})	4.00
Real transpiration/potential transpiration, end of leaf growth (.)	0.95
Real transpiration/potential transpiration, end of root growth (.)	0.50
Mean daily temperature for optimal growth, T_{opt} (°C)	18.00
Max daily water consumption, W_{maxd} (mm d^{-1})	12.00
Hydraulic leaf potential, onset of stomatal closure (J kg^{-1})	−1200.00
Hydraulic potential, leaf wilting (J kg^{-1})	−1800.00

Morphology	Val.
Max root depth, d_{Rmax} (m)	1.60
Initial green area index (m^2 m^{-2})	0.011
Max leaf area index, LAI_{max} (m^2 m^{-2})	5.00
Fraction LAI_{max} at maturity (.)	1.00
Specific leaf area *SLA* (m^2 kg^{-1})	25.00
Partition stem/leaf (m^2 kg^{-1})	2.80
Leaf duration (°C d)	750
Extinction coefficient of sun radiation (.)	0.45
Sensitivity of leaf to water stress (0–3) (.)	1.00
Evapotranspiration coefficient K_c (.)	1.19

Phenology	Val.
Degree-day emergence (°C d)	52.00
Degree-day LAI peak (°C d)	800.00
Degree-day flowering (°C d)	820.00
Degree-day at *grain filling* (°C d)	1050.00
Degree-day maturity (°C d)	1630.00
Base temperature (°C)	8.00
Threshold temperature (°C)	30.00
Phenologic sensitivity water stress (0–3) (.)	1.00

Harvest	Val.
Harvest index, no stress (.)	0.52
Sensitivity water stress flowering (.)	0.40
Sensitivity water stress flowering *grain filling* (.)	0.40
Translocation factor (.)	0.40

Data of CO_2 were gathered by the Monte Cimone (MO) observatory of Italy. *CropSyst* also simulates the effect of a change of CO_2 upon crop growth and yield. We set up a simulation with intensive maize production (no fallow), as done in the area, with sowing date April 4th, i.e. the average present date as reported by farmers.

Nitrogen was applied in the amount of 200 kg ha^{-1} (urea) 15 days before sowing, and 20 kg ha^{-1} 6 days after sowing, as normally done in Cremona province, and complying with the EU directive about Nitrates (Directive 91/676/CEE). The nitrogen budget via *CropSyst* was not simulated (i.e. N is not a limiting factor), because a preliminary investigation indicated that, given the soil composition and the manuring with nitrogen, no lack of fertilization was likely.

2.4. Crop model: CropSyst

We used the crop yield model *CropSyst* (Stöckle et al., 2003), which has been described thoroughly in several publications (Bellocchi et al., 2002; Stöckle et al., 2003). A brief description of this model is provided here. Water balance is carried out by taking inputs of precipitation *P* and irrigation (*I*), and provides as outputs soil storage (ΔS), surface flow (*Q*), sub-surface flows (*G*), evapotranspiration (*ET*), split in soil evaporation (E_s), plus crop transpiration (T_c), given as

$$P + I = \Delta S + Q + G + ET. \tag{1}$$

Crop phenology is described by way of degree-day method °C-d, i.e. by accumulation of daily temperatures (below *cutoff* value), until a given amount is accumulated to determine growth stage.

Biomass accumulation is also tracked. The amount accumulated is the smallest of daily biomass growth amounts calculated using one of two potential growth rate values. The first one is calculated using potential transpiration (*TP* in kg m^{-2} d^{-1}), given as

$$B_{PT} = \frac{K_{BT} TP}{VPD}, \tag{2}$$

where B_{PT} is biomass (kg m^{-2} d^{-1}) produced by potential transpiration, *VPD* is vapour pressure deficit (kPa) and K_{BT} is the biomass-transpiration coefficient (kPa kg m^{-3}) (Stöckle and Nelson, 1999).

Reference (potential) evapotranspiration (*ETP*) needed to calculate *TP* is estimated using Priestley–Taylor equation. Specific (to crop) potential evapotranspiration (ETP_0) is modified for the specific crop by way of a crop coefficient (K_c), or

$$ETP = ETP_0 K_c, \tag{3}$$

and then split into (potential) transpiration (*TP*) and evaporation (*EP*) via

$$\begin{aligned} TP &= ETP\, f_c \\ EP &= ETP(1 - f_c) \end{aligned}, \tag{4}$$

where f_c is the fraction of incident radiation intercepted by the crop green leaf area.

The second potential daily biomass growth is given by photosynthetically active radiation (*PAR*, in kg m^{-2} d^{-1}, Monteith, 1977), given as

$$B_{IPAR} = e_I IPAR, \tag{5}$$

where e_I is radiation efficiency (kg MJ^{-1}), and *IPAR* is total PAR as intercepted by the plant (MJ m^{-1} d^{-1}). Every day potential biomass is taken as the least of the values by of Eqs. (2) and (5). This is then converted into real biomass (B_T) as

$$B_T = \frac{B_P T_c}{TP} \tag{6}$$

where T_c/TP is the ratio of real transpiration to potential transpiration. Real transpiration (T_c) increases as a function (not shown for shortness, Stöckle and Nelson, 1999) of plant available water (*PAW*) ratio [.]

$$PAW = \frac{\theta - \theta_w}{\theta_l - \theta_w}, \tag{7}$$

where θ is soil water content [0–1], θ_w is wilting point, and θ_l is field capacity. *LAI* is calculated as a function of biomass, or

$$LAI = \frac{SLA \cdot B_T}{1 + pB_T} \tag{8}$$

where *SLA* is specific leaf area and *p* is stem/leaf partition ratio.

Yield (*Y*) [ton ha^{-1}] is the product of total biomass at maturity (B_{TM}) times harvest index (*HI*), in ideal conditions (no water stress), depending on crop type, and corrected for sensitivity to water stress during flowering and grain filling, or

$$Y = B_{TM} HI. \tag{9}$$

To model yield dependence upon CO$_2$ *CropSyst* relies upon two approaches, namely (i) Monteith's (1977) approach, which modifies e_I in Eq. (5) as a function of CO$_2$ and (ii) Tanner and Sinclair (1983) approach, which modifies K_{BT} in Eq. (2) depending upon CO$_2$. Modified versions of these approaches, tailored upon the bases of recent experimental studies, are implemented within the *CropSyst* code (Stöckle et al., 1992, 2003). Calibration parameters, their probable range, and values used in this study are reported in Table 3.

2.5. *Water footprint*

We adopted the concept of green and blue *water footprint* as originally introduced by Hoekstra (2003) and Hoekstra and Chapagain (2008), and used in studies concerning water use of agriculture (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 the quality of water involved within the production of a given good. According to Rost et al. (2008), we used (i) green *water footprint* (WF_G) and (ii) blue *water footprint* (WF_B).

Table 3

Calibration parameters *Cropsyst*, and validation statistics, absolute and percentage bias *Bi* and *Bi%*, and absolute and percentage random mean square error *RSME*, *RSME%*.

Parameters	Range	Val.
Growth reduction threshold (°C)	0–25	18
Specific leaf area (m^2 kg^{-1})	15–25	25
Partition stem/leaf (.)	1–10	2.80
Leaf duration (°C d)	700–1000	750
Evapotranspiration coefficient (.)	0.8–1.4	1.19
Degree-day emergence (°C d)	0–300	52
Degree-day LAI peak (°C d)	300–1500	870
Degree-day flowering (°C d)	300–1500	920
Degree-day at *grain filling* (°C d)	300–1500	1200
Degree-day maturity (°C d)	1000–2500	1650
Threshold temperature (°C)	0–10	10
Cutoff temperature (°C)	20–30	30

Validation statistics	MA	AU
Bi (ton ha^{-1})	−0.88	0.22
RMSE (ton ha^{-1})	2.04	0.55
Bi% (%)	−7.71	1.93
RMSE% (%)	17.63	4.84

Green *water footprint* refers to the consumption of water stored in the ground as a result of precipitation. Precipitation infiltrating in the ground remains for short periods. If this water is used for plant growth it is considered as green water. After rainfall, water wetting plant surfaces, and transpiration through stomata, are considered as green water. We evaluated WF_G by comparing evapotranspiration during the growth season (ET_g), as simulated by *CropSyst*, against the cumulative precipitation during the growing season (P_g):

$$\begin{aligned} &\text{if}\, ET_g \geq P_g \quad WF_G = P_g \\ &\text{if}\, ET_g < P_g \quad WF_G = ET_g \\ &ET_g = E_{s,g} + T_{c,g} \end{aligned} \tag{10}$$

where $E_{s,g}$ is soil evaporation and $T_{c,g}$ is transpiration from the crop during the growing season. Whenever actual evapotranspiration during the growth season exceeded precipitation during the same period, precipitation was entirely used, either productively for plant growth, or unproductively for soil evaporation. Conversely, if precipitation was higher than evapotranspiration, WF_G was estimated via the latter, i.e. we assumed that in case of abundant water income from precipitation, evapotranspiration (i.e. plant growth plus soil evaporation) was entirely sustained by precipitation. In fact, water from rainfall infiltrates into soil, and modifies water content θ, so modifying *PAW*, according to Eq. (7). *PAW* in turn regulates actual evapotranspiration. Therefore, if enough rainfall occurs, enough soil moisture is available and ET_g is entirely supplied by rainfall.

We neglected the possible mismatch between precipitation and water need during the growing season, which may decrease WF_G (because some rainfall may go lost, i.e. for runoff in periods of wet soil). However, we found out that surface runoff never exceeded 5% of precipitation on average in all our simulations (not shown), so this effect seemed negligible. 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 WF_B as

$$\begin{aligned} &\text{if } ET_g \geq P_g \quad WF_B = ET_g - P_g \\ &\text{if } ET_g < P_g \quad WF_B = 0 \end{aligned} \tag{11}$$

i.e. the actual evapotranspiration not accounted for by precipitation is the blue *water footprint*, coming from either irrigation, or soil storage, with WF_G and WF_B expressed in mm. We introduced also *specific* (green or blue) *water footprint* (WF^*) as the amount of water in kg necessary to produce 1 kg of harvested yield, namely

$$WF^*_{G,B} = \frac{WF_{G,B}}{Y} \tag{12}$$

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

$$WF^P_{G,B} = \frac{WF_{G,B}}{P_g} \tag{13}$$

We neglected the grey *water footprint* (Mekonnen and Hoekstra, 2011), making reference to the water volume required to dilute pollutants, such as fertilizers, emitted during production. Calculation of grey *water footprint* would require simulation of the mass budget of fertilizers (here nitrogen), not carried out here as reported. Also, we were interested here into climate variables, and we left investigation of manure strategies for further on.

2.6. Climate scenarios

Future climate simulations were carried out by using four GCMs, namely the Parallel Climate Model (PCM) and the Community Climate System Model (CCSM3) produced from the National Centre for Atmospheric Research at Boulder, in Colorado, the Hadley Centre Coupled Model (HadCM3), produced from the Hadley Centre for Climate Prediction and Research, and the Atmospheric General Circulation Model (ECHAM5), produced by the Max Planck Institute for Meteorology in Hamburg, Germany. We used the *storyline* A2, *business as usual*, often adopted for crop yield projections (Torriani et al., 2007).

GCMs are physically based tools presently used in predicting climate change effects (Bates et al., 1998). GCMs deliver projected meteorological variables in a fine time resolution (30 min to a few hours) but in a usually coarse spatial grid (50–500 km). Although GCMs perform reasonably well in simulating synoptic atmospheric fields, they usually reproduce poorly the statistics of historical records at the smallest spatial scales, and downscaling is required to obtain climate series that are consistent with the locally measured ones (Burlando and Rosso, 2002; Groppelli et al., 2011a). Therefore, we performed downscaling of precipitation and temperature provided by the adopted GCMs, necessary as inputs to *CropSyst*. For precipitation, we used an already developed and tested random cascade approach (Groppelli et al., 2011a). This was carried out by multiplying daily simulated GCM rainfall series by a statistical cascade generator B_iW_i, so as to obtain a rainfall series consistent with the local one. The random cascade model was calibrated using local MARS data, to obtain daily ground precipitation at day i (R_i)

$$\begin{aligned} &R_i = Bias\, R_{GCM,i} Y_i = Bias\, R_{GCM,i} B_i W_i \\ &P(B_i = 0) = 1 - p_i \\ &P(B_i = p_i^{-1}) = p_i \\ &E[B_i] = p_i^{-1} p_i + 0(1 - p_i) = 1 \\ &W_i = e^{(w_i - \sigma^2_{wi}/2)} \\ &E[W_i] = 1; w_i = N(0, \sigma^2_{wi}) \end{aligned} \tag{14}$$

where *Bias* is the multiplicative bias of GCM's precipitation as deduced from ground data, $R_{GCM,i}$ is the projected GCM's precipitation at day i, p_i is the probability of rainfall (intermittence), and σ^2_{wi} is the variance of the cascade weights, governing rainfall intensity. This method, and particularly the *Bias* term in Eq. (14), is based on the hypothesis that the difference between precipitation from the GCMs and that observed on the ground remains similar in the future. This a priori assumption, which cannot be proven when future climate is investigated, may lead to poor estimation of future precipitation.

To downscale temperatures we used a monthly averaged temperature shift (*DT*) approach as deduced from data (Groppelli et al., 2011b). Daily temperature simulated by the GCMs was therefore shifted by a proper, monthly averaged value of *DT*, so as to obtain a new daily temperature series statistically consistent with the locally observed one. Also temperature downscaling was calibrated using MARS data. Because the area is flat, no vertical lapse rate was necessary for temperature.

Concentration of CO_2 was used as provided by the GCMs upon IPCC recommendations. CO_2 changes from ca. 400 ppm in 2010 to ca. 800 ppm in year 2100, similarly for all GCMs (with a value of 531 ppm on average during 2045–2054). Only average yearly values were provided by the adopted GCMs, and daily variation is not likely to be important, so no downscaling procedure was carried out. The GCM models do not provide simulation of future solar radiation, so we used the observed values of R_S during 2001–2010.

A local scenario (LOC) was built by projections of linear trends of the variables T_{max}, T_{min}, P and CO_2, as evaluated using the *MARS* time series for a 36 years period (1975–2010).

3. Results and discussion

3.1. Crop yield and water footprint

We made several test runs of *CropSyst*, to tune model parameters so as to obtain yield data as much as possible coherent with those given by ISTAT. We continuously simulated soil water balance (and crop growth during the growth season) with *CropSyst* from January 1st 2001 to December 31st 2010, to keep into account water storage dynamics for the whole period. We chose alternately the option of manual irrigation, or automatic irrigation. In Fig. 2a we report the best simulation in the tuning phase, while in Table 3 we report model validation statistics, namely absolute and percentage bias (*Bi*, *Bi%*), and absolute and percentage random mean square error (*RSME*, *RSME%*). ISTAT yield data were pretty much constant except for 2003, when high temperature and low precipitation occurred during the growth season, which reduced maize production. Average yield during 2001–2010 was 11.43 ton ha^{-1}. Manual irrigation MA provided acceptable agreement (*Bi* = −0.88 ton ha^{-1}, *RSME* = 2.04 ton ha^{-1}, *Bi%* = −7.71%, *RSME%* = 17.63%), except for 2006, when CropSyst simulated lower yields than the ISTAT data. The model simulated water stress during the growing season (not shown), resulting in low yield. Thus, the 250 mm of water we assumed was applied in 2006 based on farmer interviews was not enough to sustain maize plants during 2006. Automatic irrigation AU provided a yield closer to the ISTAT one during 2006. This is because AU option better interprets the likely behaviour of a farmer, who in the presence of a drier than usual season would water the crop field with more water than the average amount, which probably happened during 2006.

The AU results delivered a yield closer to that of ISTAT data on average (11.66 ton ha^{-1} vs. 11.45 ton ha^{-1}, *Bi* = 0.22 ton ha^{-1}, *RSME* = 0.55 ton ha^{-1}, *Bi%* = 1.93%, *RSME%* = 4.84%). This was due to the *CropSyst* model being able to evaluate optimal timing and amount of irrigation better than farmers, however expert. However,

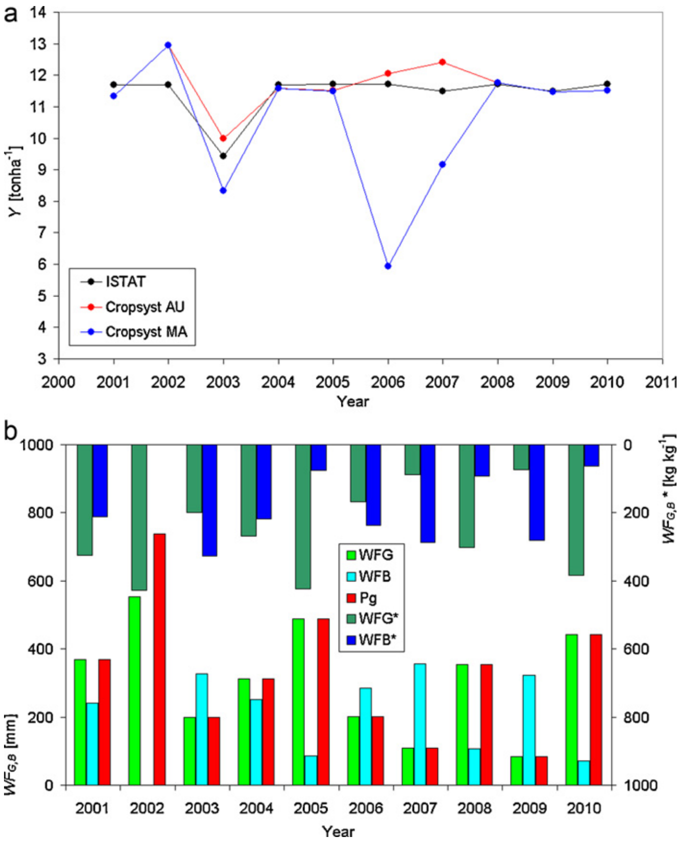

Fig. 2. *Cropsyst* calibration, control period 2000–2010. (a) Crop yield and (b) water footprint.

with AU option, the average yearly yield and its variability (coefficient of variation 0.066 vs. 0.062) were similar, and we assumed that the model reproduced well maize growth dynamics. With this in mind, we estimated reasonably the *water footprint* of the crop, reported in Fig. 2b as per the ten reference years, both in absolute value $WF_{G,B}$, and specific to crop yield $WF^*_{G,B}$. Also we report reference precipitation during the growth season (P_g) next to WF_G. Clearly, in most cases, WF_G coincided with the whole seasonal rainfall, except for those years with considerable precipitation. When P_g was low, clearly WF_B was higher, and evapotranspiration necessary for plants' life cycle was sustained by irrigation, and by previous soil water content. When P_g was bigger than WF_G clearly WF_B was null (e.g. year 2002). When considering $WF^*_{G,B}$, some difference was seen. In those years when yield was higher than normal (e.g. year 2002, $Y = 12.9$ ton ha^{-1}, and 2007, $Y = 12.4$ ton ha^{-1}), $WF_{G,B}$, albeit higher in absolute value than those in other years, became closer to average when made specific to yield. This indicates that when a high yield is attained use of water is more efficient.

3.2. Sensitivity analysis to climate

To evaluate the most relevant weather variable for crop yield and *water footprint*, and to be able to better interpret effects of climate change scenarios, we carried out a sensitivity analysis, by changing one variable at a time according to possible ranges suggested in the present literature. We considered three weather variables which hold influence upon crop growth and yield. These are (i) temperature (+2 °C, +4 °C, +6 °C), (ii) precipitation (−20%, −10%, +10%, +20%), (iii) CO_2 concentration in the atmosphere (+10%, +20%, +30%). Starting from the present environment, or control run CO, we evaluated the outcome when each of these three variables is modified. We also considered the three irrigation options NO, MA, and AU, because we wanted to highlight the effect of irrigation practice, under potentially different climate conditions. In Table 4 we report yield and water footprint under modified weather. All other agricultural parameters remained unchanged. Increasing temperature resulted into decreasing WF_G (i.e. precipitation used was less), but in increasing WF_B. However, yield also decreased, so that $WF^*_{B,G}$ was higher than that for CO under any irrigation option. The reason for such behaviour is found by examining harvest dates (not shown), which came earlier with higher temperatures. Clearly, higher temperatures provided quicker saturation of the degree-days available for the crop, so making maturation rapider. However, given the shorter available time, total evapotranspiration was reduced (so lower $WF_{B,G}$), and yields were less (so more $WF^*_{B,G}$), with a net negative effect.

The effect of increasing CO_2 was to decrease *ET* (by way of stomatal closure) and to increase biomass production efficiency, so that eventually $WF_{G,B}$ decreased (slightly), and Y increased, with net, albeit small, decrease of $WF^*_{B,G}$. Decreasing precipitation resulted into decreased WF_G, compensated by increasing WF_B, especially under the MA and AU irrigation options. Under the NO option yield decreased due to less rainfall, uncompensated for by flooding irrigation. With increasing precipitation, WF_G and Y increased, and WF_B decreased accordingly.

3.3. Weather scenarios

The four different GCMs models (A2 storyline) and the local scenario adopted here provided different depictions of future climate. Table 5 gives a summary of significant weather variables under the considered scenarios. The PCM model projected a slight increase (with respect to CO scenario 2001–2010) of average precipitation in the growing season (ΔP_g) during 2045–2054 ($\Delta P_g = +67$ mm), and HADCM3 projected instead a heavily increased precipitation ($\Delta P_g = +191$ mm). The CCSM3 and ECHAM5 models projected decreased precipitation instead ($\Delta P_g = -137$ mm, and $\Delta P_g = -91$ mm, respectively). All models projected increasing temperatures, albeit with different rates (from +0.5 °C for PCM to +2.4 °C for CCSM3).

The LOC scenario provided a reference simulation based upon the observed trends of the considered weather variables, to compare against the GCM scenarios (Groppelli et al., 2011b). We found a noticeable decrease of P during all season, and especially Summer (i.e. maize growth season), as reported in Table 5 ($\Delta P_g = -206$ mm in 2045–2054 vs. 2001–2010). Temperature T_{min} and T_{max} increased, especially during summer. Concerning CO_2, LOC values, which we projected from observed data at the Monte Cimone observatory as reported, were lower than those projected by the models (455 ppm on average during 2045–2054). Notice that projection of single weather (or air chemistry) variables based upon linear extrapolation from data is of course improper, and one expects that GCM projections are more physically accurate. Still, we used this LOC scenario to (i) be able to acknowledge those GCM results that are more likely to provide future scenarios closer to local climate and (ii) evaluate what the impact upon crop and *water footprint* would be if future weather would follow recently observed trends, under a *what if* perspective.

3.4. Yield and water footprint scenarios

We evaluated modified crop yield and water footprint scenarios under climate change. In Table 6 and Fig. 3 we report modified crop yield under the considered scenarios, and based upon our three irrigation options. In Figs. 4 and 5 we report, respectively, statistics (average, standard deviations) of (i) water footprint in absolute and specific terms, and (ii) water footprint relative to precipitation.

Table 4
Weather sensitivity analysis of crop yield and water footprint. Average *E* [–], and coefficient of variation CV [–] due to variation of weather variables. *Y* is yield. NO is no irrigation, MA is manual irrigation, AU is automatic irrigation. WF_G is green water footprint, WF_B is blue water footprint.

Var.	NO	*E* [*Y*] (ton ha^{-1})	CV[*Y*] (.)	MA	*E* [*Y*] (ton ha^{-1})	CV[*Y*] (.)	AU	*E* [*Y*] (ton ha^{-1})	CV[*Y*] (.)
CO_2	+10%	6.21	0.60	+10%	10.79	0.19	+10%	11.84	0.07
	+20%	6.60	0.60	+20%	11.08	0.17	+20%	12.00	0.07
	+30%	6.96	0.59	+30%	11.39	0.16	+30%	12.15	0.07
T	+2 °C	5.07	0.55	+2 °C	8.97	0.21	+2 °C	9.89	0.06
	+4 °C	4.76	0.54	+4 °C	7.64	0.24	+4 °C	8.54	0.07
	+6 °C	4.16	0.52	+6 °C	6.51	0.21	+6 °C	7.23	0.09
P	+10%	6.60	0.60	+10%	10.73	0.18	+10%	11.65	0.07
	+20%	10.90	0.16	+20%	10.94	0.15	+20%	11.65	0.07
	−10%	4.96	0.54	−10%	10.32	0.22	−10%	11.65	0.07
	−20%	3.84	0.47	−20%	9.92	0.27	−20%	11.65	0.07
CO	–	5.90	0.60	–	10.55	0.20	–	11.65	0.07

Var.	NO	E [WF_G] (mm)	CV[WF_G] (.)	MA	E [WF_G] (mm)	CV[WF_G] (.)	AU	E [WF_G] (mm)	CV[WF_G] (.)
CO_2	+10%	295	0.48	+10%	311	0.51	+10%	311	0.51
	+20%	295	0.48	+20%	310	0.51	+20%	310	0.51
	+30%	295	0.48	+30%	309	0.50	+30%	309	0.50
T	+2 °C	273	0.49	+2 °C	283	0.51	+2 °C	284	0.51
	+4 °C	247	0.48	+4 °C	252	0.51	+4 °C	254	0.50
	+6 °C	232	0.49	+6 °C	233	0.49	+6 °C	233	0.49
P	+10%	321	0.47	+10%	337	0.50	+10%	337	0.50
	+20%	345	0.46	+20%	361	0.48	+20%	361	0.48
	−10%	267	0.48	−10%	286	0.54	−10%	286	0.54
	−20%	238	0.49	−20%	260	0.57	−20%	260	0.57
CO	–	294	0.54	–	311	0.41	–	311	0.49

Var.	NO	E [WF_B] (mm)	CV[WF_B] (.)	MA	E [WF_B] (mm)	CV[WF_B] (.)	AU	E [WF_B] (mm)	CV[WF_B] (.)
CO_2	+10%	92	0.74	+10%	181	0.62	+10%	197	0.64
	+20%	92	0.74	+20%	177	0.65	+20%	190	0.66
	+30%	92	0.76	+30%	173	0.68	+30%	182	0.68
T	+2 °C	92	0.77	+2 °C	176	0.62	+2 °C	194	0.63
	+4 °C	103	0.62	+4 °C	172	0.51	+4 °C	193	0.54
	+6 °C	109	0.50	+6 °C	168	0.43	+6 °C	191	0.49
P	+10%	86	0.82	+10%	168	0.73	+10%	182	0.74
	+20%	80	0.94	+20%	151	0.87	+20%	160	0.87
	−10%	95	0.70	−10%	203	0.53	−10%	228	0.53
	−20%	96	0.68	−20%	216	0.49	−20%	250	0.47
CO	–	93	0.84	–	187	0.66	–	205	0.63

The LOC scenario (Fig. 3) resulted in lower yield (vs. CO scenario), due to increased temperature (Table 5), and shorter growth season, with harvest date about 20 days earlier (see harvest date, Table 6), due to quicker saturation of the degree-days for plant growth. The scenario without irrigation was particularly harsh, resulting in *Y* less than half the CO scenario, while irrigation helped to increase yield considerably (albeit lower than CO).

The LOC scenario produced low values of WF_G (Fig. 4a), consistent with considerably low precipitation during growth season (Table 5), and consequently increased values of WF_B. Specific values WF_G^* (Fig. 4b) were high, and almost equal to CO scenario in the no irrigation case, and lower for MA and AU scenarios. WF_B^* were higher as expected. Relative water footprint $WF_{G,B}^P$ (Fig. 5) was higher than in the CO scenarios for each irrigation option, implying that increasingly more water (with respect to seasonal rainfall) would be necessary for maize cropping under the LOC climate. Increase of CO_2 under the LOC scenario may provide slightly more efficient use of water according to our sensitivity analysis, but here such effect was likely hidden by temperature and rainfall dynamics.

The CCSM3 scenario (Fig. 3) also produced lower yield, due again to increased temperature, and shorter growth season, with harvest date about 11 days earlier. The scenario without irrigation was less critical than the LOC scenario. Notice also considerably wide standard deviation of *Y*, indicating higher variability due to climate, because events of water stress occurred (i.e. NO and MA case, not shown), especially when irrigation was not on demand. CCSM3 also displayed low values of WF_G in response to low precipitation during growth season (Table 5), and consequently increased values of WF_B. Specific values WF_G^* were lower than CO scenario in all

Table 5
Average values of weather variables during growth season for 2001–2010 (*control run* CO), and 2045–2054 (scenarios LOC and four GCMs models). T_{max} is maximum daily temperature, T_{min} is minimum daily temperature, P_g is cumulative precipitation, and CO_2 is carbon dioxide concentration.

Var/Scen.	CO	LOC	CCSM3	PCM	HADCM3	ECHAM5
T_{max} (°C)	19.00	21.09	21.40	19.46	20.5	20.8
T_{min} (°C)	9.64	12.74	11.81	9.87	11.14	11.44
P_g (mm)	324	118	187	391	515	233
CO_2 (ppm)	381	455	531	531	531	531

Table 6
Crop yield scenarios. Average harvest date, average *E* [–], and coefficient of variation CV [–] of yield. *Y* is yield. NO is no irrigation, MA is manual irrigation, AU is automatic irrigation.

Par./Scen.	CO	LOC	CCSM3	PCM	HADCM3	ECHAM5
NO						
Harvest date (.)	August-29	August-7	August-18	August-31	September-2	August-24
$E[Y]$ (ton ha^{-1})	5.90	2.32	5.07	9.77	11.14	4.96
CV[Y] (.)	0.60	0.36	0.37	0.31	0.23	0.51
MA						
Harvest date (.)	September-1	August-8	August-19	September-1	September-3	August-27
$E[Y]$ (ton ha^{-1})	10.54	7.59	9.77	11.81	12.08	11.64
CV[Y] (.)	0.20	0.23	0.26	0.12	0.10	0.19
AU						
Harvest date (.)	September-1	August-8	August-19	September-1	September-3	August-26
$E[Y]$ (ton ha^{-1})	11.66	8.74	10.21	12.01	12.08	12.18
CV[Y] (.)	0.07	0.05	0.22	0.10	0.10	0.13

irrigation cases, and compensated for by WF_B^*, always higher than CO. Relative $WF_{G,B}^P$ was also higher than in the CO scenarios for each irrigation option, and water used for crop was ca. 150% more than the seasonal rainfall.

The PCM scenario produced higher yields, especially for NO and MA irrigation options, and harvest date was unchanged. Standard deviation was small, i.e. crop yield was stable in time. WF_G was clearly higher than in the CO scenario, because P_g was comparatively higher, so WF_B decreased. Specific values WF_G^* were lower than CO scenario under no irrigation, and higher under MA and AU scenario, because yield under no irrigation increased considerably (Table 5, 9.77 ton ha^{-1} vs. 5.90 ton ha^{-1}). Blue WF_B^* was low, because natural rainfall may have been able to sustain most of plant growth. Relative $WF_{G,B}^P$ was clearly lower than in the CO scenarios for each irrigation option, and water used was ca. 50% more of the seasonal rainfall.

Under the HADCM3 scenario yield was even higher than PCM, especially for NO irrigation option, and harvest date only two days later than in the CO scenario. Standard deviation was again small, i.e. crop yield was stable. WF_G was higher than CO as due to high P_g, so WF_B decreased. Specific values WF_G^* were lower than CO scenario under no irrigation, and higher under MA and AU scenario, because again here yield under no irrigation increased considerably (Table 5, 11.14 ton ha^{-1} vs. 5.90 ton ha^{-1}). Blue WF_B^* was low, because natural rainfall may have been able to sustain most of plant growth. Relative $WF_{G,B}^P$ was much lower than in the CO scenarios for each irrigation option, and water used is no more than 18% in excess of the seasonal rainfall.

The ECHAM 5 scenario produced lower yield than the CO scenario under no irrigation, but higher yield under the MA and AU options, and a slightly shortened growth season (harvest date about 5 days earlier). While ECHAM5 simulated less precipitation during the year and the growing season, analysis of temperature patterns (not shown for shortness) displayed an increase above average during Spring (AMJ) and the onset of Summer in July, and a slight decrease during August, i.e. during the end of growth season. Therefore, when water was supplied to support evapotranspiration (i.e. MA and AU options), on average plants were less prone to temperature stress during their last month, and a final higher yield was obtained on average, in spite of the slightly shorter growth period. Notice however the considerably high standard deviation of yield under ECHAM5 scenario in Fig. 3, indicating that lack of water and high temperature during the warmest months of June and July may have still hampered crop growth in some years (CV[Y] = 0.13 vs. CV[Y] = 0.05 for CO). Green water footprint WF_G decreased due

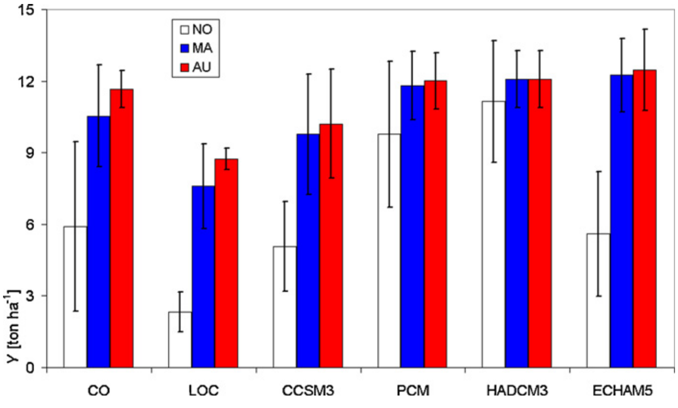

Fig. 3. Crop yield scenarios during 2045–2054. Average upon the decade and standard deviation bars. NO is no irrigation, MA is manual irrigation, AU is automatic irrigation.

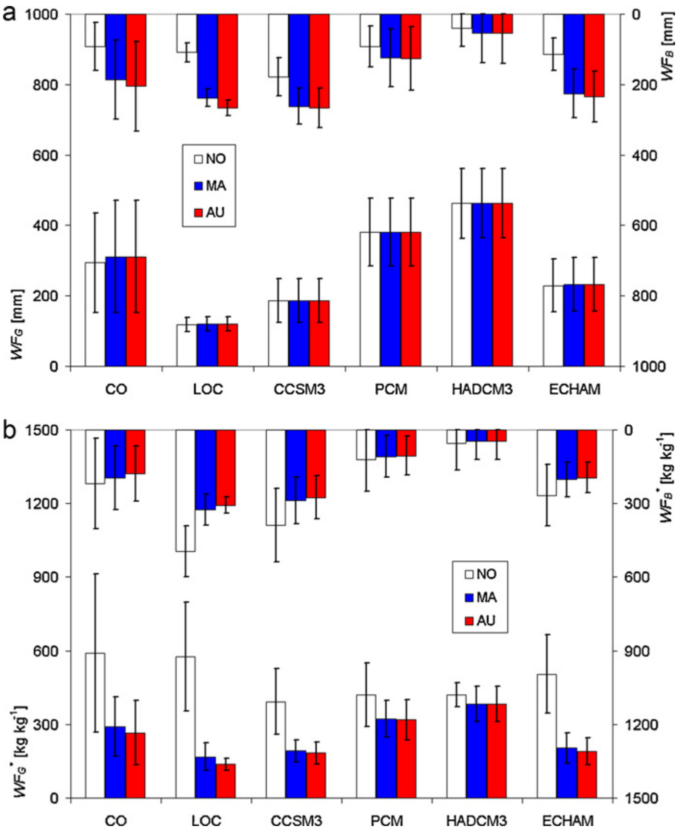

Fig. 4. Water footprint scenarios during 2045–2054. Average upon the decade and standard deviation bars. NO is no irrigation, MA is manual irrigation, AU is automatic irrigation. (a) WF_G, WF_B. (b) WF_G^*, WF_B^*.

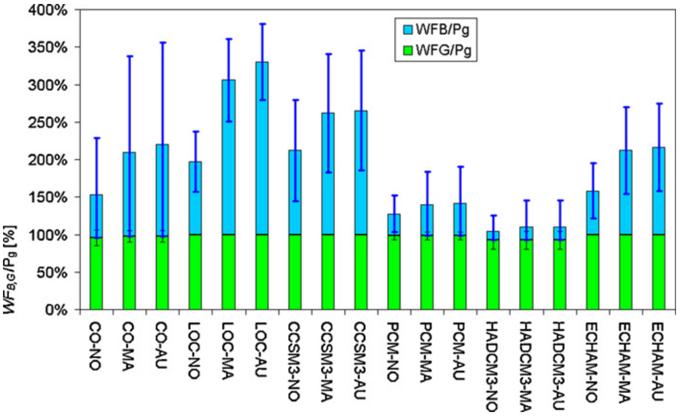

Fig. 5. Scenarios of water footprint to precipitation ratio during 2045–2054. Average upon the decade and standard deviation bars. NO is no irrigation, MA is manual irrigation, AU is automatic irrigation.

to low precipitation during growth season, and WF_B was always increasing. Specific values WF_G^* were lower than CO scenario in all irrigation cases, and compensated for by WF_B^*, always higher than in the CO scenario. Relative $WF_{G,B}^P$ was very close to the CO scenario for each irrigation option, and lower than for LOC and CCSM3, and water used for crop may be as much as 120% more than the seasonal rainfall.

3.5. Discussion

Our study of *water footprint* and impact of possible climate change until 2050 within the Persico Dosimo site, representative of the agricultural area of Po valley, displayed some interesting results. For a moderate increase of temperature (PCM, HADCM3, ECHAM5, $\Delta T < 2\,^{\circ}$C) cereal crops (here, maize) still provided equivalent (or slightly increased) yield in spite of decreasing rainfall. This was attained if either rainfall increased or abundant irrigation was provided, as in the case of ECHAM5 model. However, with higher temperatures, greater fluctuations were seen, even when irrigation on demand was considered (Table 6, CO, CV[Y] = 0.07, PCM, CV[Y] = 0.10, HADCM3 CV[Y] = 0.10, ECHAM5, CV[Y] = 0.13). Clearly enough, when higher precipitation occurred (PCM, HADCM3) less irrigation was necessary, so decreasing the need for water, other than seasonal rainfall. Because yields were still acceptable on average, the specific blue *water footprint* decreased. This made the total amount of water necessary close to total seasonal rainfall, and the maize crop more sustainable in this sense. When lower precipitation occurred (ECHAM5), irrigation could still make up the difference, and provided an acceptable yield, at the cost of decreasing local sustainability, i.e. increasing absolute blue water consumption, with a constant specific value of *water footprint*. When temperature increased more (LOC, CCSM3 $\Delta T > 2\,^{\circ}$C) even on demand irrigation was not enough to sustain an equivalent yield. Decreased precipitation under the LOC and CCSM3 scenarios strongly increased the specific blue *water footprint*. Relative water usage $WF_{G,B}^P$ became very high under this scenarios, and irrigation was as much as 230% (LOC, 165% CCSM3) of seasonal rainfall to obtain the greatest possible yield, which in turn was still 25% less (LOC, −12% CCSM3) than optimal yield now. Increase of CO_2, albeit able to slightly decrease both absolute and specific $WF_{G,B}$ under each irrigation scenario, seemed not to impact heavily either yield or *water footprint* in our target area according to our sensitivity analysis, so we conclude that it does not carry a significant bearing upon our crop yield and water footprint projections, at least within the first half of this century, and that temperature and precipitation signal is more relevant.

Use of a decadal reference periods as carried out here (2001–2010 vs. 2045–2054) may not provide a long enough series to assess robust statistics. The proposed water footprint scenarios supply a range of possible situations that scientists and planners will have to expect in the future evolution of water resources usage for cropping of maize in the Po valley. A remarkable source of uncertainty is laid within the determination of the future trends of precipitation in the area, which is subject of a considerable debate.

Brunetti et al. (2006) studied the presence of trends of yearly precipitation P_{CUM} in the greater alpine region GAR, including the case study area here, using long term observations from 192 stations. The authors highlighted four different regions, displaying somewhat variable behaviour. Particularly, the Persico Dosimo here is clearly within their region South-East (EOF-2 in their Fig. 4), where decreasing P_{CUM} was found. Faggian and Giorgi (2009) have studied recent projections of precipitation supplied from 20 different *GCMs* model (including PCM, HADCM3, ECHAM5 and CCSM3 here) for the greater alpine region GAR until 2100. With reference to period 1961–90, the authors report possible variations (A1B, A2, B1 storylines) of P_{CUM} for the decade 2045–2054 ranging between −10% and +10% approximately, with a variability reaching −15% in Italy, strongly inhomogeneous in space (e.g. Fig. 5, Faggian and Giorgi, 2009). Po valley is clearly indicated therein as a hotspot for possible climatic droughts, and until 2071–2100 the authors projected a strong reduction (−30% to −50% vs. 1961–1990) of total precipitation during Spring and Summer. Faggian and Giorgi (2009) also projected (2050) an average increase of temperature of ca. +2 °C (vs. 1961–1990) for the GAR, and again they find a hotspot in the Po valley (+2–3 °C during Spring for 2071–2100, +5–6 °C in Summer for 2071–2100). Despite the considerable uncertainty in actual figures, the analysis of the present literature and of the local data (i.e. scenario LOC), displaying recently (1975–2010) increasing temperatures and decreasing precipitation in our target area, delivers a clear picture.

Cropping systems of Europe and Italy have been studied (Leuning, 1995; Jarvis et al., 1999; Tubiello et al., 2007; Soussana et al., 2010) by way of crop models providing measurable performance (Donatelli et al., 1997; Confalonieri et al., 2009, 2011), and cropping water consumption against availability has been explicitly investigated (e.g. for wheat, Aldaya and Hoekstra, 2010).

Among others, Supit et al. (2010) used data from the Crop Growth Monitoring System to evaluate potential crop yields during 1976–2005 for a number of crops including maize, for 24 countries in Europe. In Northern Italy, and especially in Lombardia and Po valley, they highlighted decreased crop yield for wheat, barley and maize (the latter down to −0.05 ton ha^{-1} year^{-1}). Here, for the rain fed simulation we obtained (Table 6) a lapse rate ranging from −0.08 ton ha^{-1} year^{-1} (LOC, with the lowest precipitation during growth season P_g, −4.6 mm year^{-1}) to +0.12 ton ha^{-1} year^{-1} (HADCM3, with P_g +4.24 mm year^{-1}). Considering (manual) irrigation one has −0.07 ton ha^{-1} year^{-1} for LOC, and +0.03 ton ha^{-1} year^{-1} for HADCM3.

Tubiello et al. (2000) used projected climate scenarios from two GCMs to simulate prospective modified yield mass of a 3-year maize–maize–wheat rotation systems in Modena (Po valley, Northern Italy), demonstrating that the effects of an increased atmospheric CO_2 with higher temperatures, would depress crop yields if current management practices were not modified. Also, they found that warmer air would accelerate plant phenology, reducing dry matter accumulation and crop yields by 10–40%. They suggested adaptation strategies, showing that a combination of early planting for Spring–Summer crops and use of slower-maturing cultivars may maintain crop yields at current levels. However, they would assume unlimited water availability, which is unlikely under increased evapotranspiration conditions as given by higher temperatures, and decreased fresh water supply as expected under climate change conditions in the Po valley.

Torriani et al. (2007) investigated the impact of climate change upon maize productivity in Switzerland. They used 2071–2100 climate projections from the Danish Meteorological Institute regional climate model HIRHAM4, under A2 scenario of the IPCC. They found potential crop yield decrease in response to decrease in the long-term mean of seasonal precipitation. Earlier sowing dates were found to reduce the negative impact of climate change on yield stability, but it was not sufficient to ensure average productivity levels comparable to those now.

Our results show clearly that under a likely future climate scenario with higher temperatures and less precipitation, more blue water, i.e. water from irrigation will be necessary in our study site, and by extension in the Po valley. Even at constant specific values of WF_B^*, more water will be needed. The increasing ratio of blue water necessary, with respect to seasonal precipitation (i.e. green water) may be taken as a clue of the loss of sustainability of the crop, which clearly will require much more water than is naturally available, to provide a reasonable yield.

As reported, Po valley is one of the most productive agricultural areas within Europe, and proper crop management under climate change impact must be tackled soon enough. Maize, extensively cultivated here, meets its most demanding period for irrigation during Spring and Summer, from water supplied by several lakes and reservoirs fed by stream flows from Alpine catchments (Galelli et al., 2010), which will need to increase under future climate change conditions. Recent studies have demonstrated that transient climate change within the next half century will likely lead to dramatically decreased Summer flows from rivers in Northern (Bavay et al., 2009) and Southern Alps (Anghileri et al., 2011; Groppelli et al., 2011b), so diminishing available water for irrigation, and cascading into enhanced conflicts in use of irrigation water within schemes of reservoir's management for multiple purposes, i.e. hydro-power, flood dampening, ecological flows (Soncini et al., 2011). The highlighted topics point altogether to a scenario where cropping of maize (and other cereals) will be more and more demanding, i.e. less and less sustainable, given the boundary conditions of water availability.

Such increased water demand will impact *virtual water trade*, i.e. the commerce of *virtual water* embedded in goods (maize) that are sold or bought, and specifically, under climate change conditions countries in temperate climate selling their crops will deliver more and more water with them. Planning of national and international crop trade will have to take into account such facet soon.

Water footprint of maize (as of any other crop), either absolute, specific to yield, or relative to precipitation, is therefore an objective indicator of how much water is necessary to produce a given crop, and can be used as (i) a measure of sustainability of cropping in the study area, (ii) a measure of the fallout of climate change upon crop efficiency and sustainability, (iii) an indicator of performance of adaptation schemes, and (iv) a measure of virtual water trade when crop is sold or bought.

Model parameterization here, albeit carried out here accurately as possible, may impact the projections. Different storylines from the investigated *GCMs* models (e.g. A1B, B1) may provide slightly different results, and will be investigated in the future.

Here, we did not consider adaptation strategies for lack of room, but several are available in the present cropping practice (e.g. modified sowing date, use of different cultivars, etc.), and some have been studied within literature (Tubiello et al., 2000; Torriani et al., 2007). We preliminarily evaluated the effect of anticipated sowing dates by one or two weeks (not shown), but these measures would not provide significant changes of either Y or $WF_{G,B}$. In the future, more efficient adaptation strategies will need be implemented, and their performance measured by way of objective indicators, including water footprint and related indexes, as displayed here.

4. Conclusions

We used here a sophisticated state of the art crop yield model to accurately evaluate water footprint of a particular, water demanding crop species widely diffused in Northern Italy. We then carried out an experiment concerning impact of climate change upon *water footprint*, little studied, if ever, in our knowledge. We demonstrated here that climate change as projected by reference climate models in the available literature may modify considerably *water footprint* of Po valley maize fields, either positively (i.e. with less need of irrigation, in case more rainfall would occur in growth season), or more likely negatively (i.e. when less rainfall should show up, as found out by screening of local data and studies in the literature). Total (green or blue) specific (kg kg^{-1}) water consumption (green + blue) for crop is projected to vary slightly with reference to the control scenario (−13% for ECHAM to +3% for LOC, lowest and highest for automatic irrigation).

However, while specific blue water footprint would decrease by −74% for HADCM3, with considerable precipitation increase, under the LOC scenario with decreasing precipitation, it would increase to +71%, indicating the possible need for heavily increased irrigation in the future.

The ratio of blue water footprint to precipitation during growth season, $W_B{}^P$, would be 18% for HADCM3 and 230% for LOC, against 123% in the CO scenario, showing how maize production would be less and less suitable for sole rain feeding in a future drier climate.

The proposed study provides results that are of interest on their own, given the importance of the case study area, and further provide a template usable by other scientists to (i) investigate objectively *water footprint* of a particular crop in a specific site based upon detailed modelling, (ii) evaluate climate change impact therein, (iii) benchmark objectively adaptation strategies, aimed to decrease absolute or specific *water footprint*, and (iv) accurately estimate *virtual water* trade under different climate scenarios. Eventually, our results deliver a possibly 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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