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Modelling Mediterranean agro-ecosystems by including agricultural trees in the LPJmL model

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Abstract. In the Mediterranean region, climate and land use change are expected to impact on natural and agricultural ecosystems by warming, reduced rainfall, direct degradation of ecosystems and biodiversity loss. Human population growth and socioeconomic changes, notably on the eastern and southern shores, will require increases in food production and put additional pressure on agro-ecosystems and water resources. Coping with these challenges requires informed decisions that, in turn, require assessments by means of a comprehensive agro-ecosystem and hydrological model. This study presents the inclusion of 10 Mediterranean agricultural plants, mainly perennial crops, in an agro-ecosystem model (Lund-Potsdam-Jena managed Land – LPJmL): nut trees, date palms, citrus trees, orchards, olive trees, grapes, cotton, potatoes, vegetables and fodder grasses.

The model was successfully tested in three model outputs: agricultural yields, irrigation requirements and soil carbon density. With the development presented in this study, LPJmL is now able to simulate in good detail and mechanistically the functioning of Mediterranean agriculture with a comprehensive representation of ecophysiological processes for all vegetation types (natural and agricultural) and in a consistent framework that produces estimates of carbon, agricultural and hydrological variables for the entire Mediterranean basin.

This development paves the way for further model extensions aiming at the representation of alternative agro-ecosystems (e.g. agroforestry), and opens the door for a large number of applications in the Mediterranean region, for example assessments of the consequences of land use transitions, the influence of management practices and climate change impacts.

1 Introduction

The Mediterranean region is a transitional zone between the subtropical and temperate zones, with high intra- and inter-annual variability (Lionello et al., 2006). This region has been identified as one of the regional climate change hotspots, with a high likelihood of experiencing more frequent and more intensive heat waves, often combined with and strengthened by more intensive and longer droughts (IPCC, 2012; Kovats et al., 2014; Diffenbaugh and Giorgi, 2012). This will likely have adverse implications for the food and energy producing sectors as well as for human health, tourism, labour productivity and ecosystem services (Kovats et al., 2014; Skuras and Psaltopoulos, 2012). However, climate change is only a part of the challenges that the Mediterranean region will face in the near future. Environmental degradation involving soil erosion, biodiversity loss and pollution is negatively affecting natural and societal systems and is expected to intensify even more in future due to urbanisation, industrialisation and population growth (Doblas-Miranda et al., 2015; Lavorel et al., 1998; Scarascia-Mugnozza et al., 2000; Schröter et al., 2005; Zdruli, 2014).

Most aspects of climate change and environmental degradation will affect the Mediterranean agricultural sector directly. Agriculture plays a very important role, not only for food security in the region itself, but also through its economic integration in other regions, such as through the significant export of products to the rest of Europe (Hervieu, 2006). Agriculture therefore plays a key role for the national economies, making a part of the rural population rely on it for their livelihood and creating linkages with other issues and sectors, such as culture and tourism (Verner, 2012; Hervieu, 2006). Human population growth and socioeconomic developments on the eastern and southern shores as well as the already high dependence of the region on the international food markets will increase the need for local food production. Additionally, potential resource allocation trade-offs, especially for water and land, will put Mediterranean agriculture under increased pressure, calling for more and more efficient production practices (Verner, 2012; World Bank, 2013).

To support adaptation and mitigation efforts for climate change and environmental degradation, Mediterranean-wide assessments of the state of agriculture and the likely consequences of global change are required. These would have to be complemented by analyses of the potential developments and future difficulties of the agricultural sector and its interactions with the environment. The large-scale character of such assessments and the necessity of looking into possible future scenarios require the utilisation of modelling tools that cover the essential characteristics of the dominant agro-ecosystems in the region. At present, no suitable modelling framework for this task exists. Given the range of conditions in the region, such a tool should be process-based and integrate the major crop types, grasslands and natural vegetation, taking into account the carbon cycle and hydrology of them. Notably, the presence of perennial, woody species is a characteristic of Mediterranean agro-ecosystems, and they deliver 45 % of agricultural outputs (Lobianco and Esposti, 2006). Existing crop models have implemented some tree crops, and in some cases applications in Mediterranean environments (mostly small scale) were published. For example, the STICS crop model has been used to simulate the growth of vineyards and apple trees (García de Cortázar-Atauri, 2006; Nesme et al., 2006; Valdés-Gómez et al., 2009); and in the CropSyst model, pears, apples, vineyards and peaches are included (Marsal et al., 2013, 2014; Marsal and Stöckle, 2012). Other modelling frameworks offer general and specific formulations for horticultural systems that have been applied in other regions, mainly in Anglo-Saxon countries. This is the case for the EPIC/SWAT/SWIM families (Neitsch et al., 2004; Gerik et al., 2014) for cotton and apple, and for the APSIM model for cotton and vineyards (Holzworth et al., 2014). In California, another region with a Mediterranean climate, there is a dynamic modelling community assessing climate change impacts on horticulture by process-based (Gutiérrez et al., 2006) and empirical models (Lobell et al., 2007). At the global scale, the GAEZ approach offers potential growing areas for citrus, olives and cotton (IIASA/FAO, 2012). The GCWM model is probably the most complete model in terms of perennial crops, comprising citrus, cotton, date palm and grapes (Siebert and Döll, 2008, 2010). Other authors have developed models for fruit trees, such as the inclusion of kiwi, vineyards and apples in the SPASMO model (Clothier et al., 2012), walnuts in CAN-WALNUT (Baldocchi and Wong, 2006) and date palm by Sperling (2013). A model by Villalobos et al. (2013) focuses on transpiration of apricot, apple, citrus, olive, peach, pistachio and walnut trees.

The goals of these applications are diverse, from simple reproduction of experiments, via epidemiological analysis (causes and patterns of diseases), to the simulation of phenological change and the influence of management practices on agricultural production. Concerning the impacts of climate change, Moriondo et al. (2015) presented a detailed review of empirical and process-based models for olives and vineyards. They concluded that process-based models are better suited for climate impact studies, but they have to be completed and improved to account for the perennial nature of these crops, the effect of higher CO_2 on the atmosphere, dynamic growing periods and the effect of management practices.

Reviewing the existing studies reveals two important points. First, there is no single model or model family comprising all major agricultural plants of the Mediterranean region. Second, there is no model combining dynamic simulation of natural vegetation and agro-ecosystems for the Mediterranean region. Some models are very advanced in some processes, like the case of STICS for biochemical cycles. Other models have unique features, such as the detailed consideration of hydrology in the unsaturated zone, salt and leaching transport in the WOFOST model coupled with the SWAP and PEARL models (Kroes and Van Dam, 2003). The CENTURY model, which focuses on soil organic carbon computation, offers a forest module and general formulations that can be adapted to horticulture, but only one small-scale application was presented for the Mediterranean region (Álvaro-Fuentes et al., 2011). Without the integrated modelling of natural vegetation and agro-ecosystems in a comprehensive framework, there are many questions that cannot be answered. Notably, some of them are of extreme relevance for the Mediterranean region and concern water requirements and availability for the agricultural sector, sustainable food production potentials under climate change, environmental consequences of land use (including biodiversity loss), and soil carbon sequestration patterns, including responses to land use change.

To better assess the potential responses of Mediterranean agro-ecosystems to these forcings, we have extended the representation of Mediterranean agriculture in the Lund-Potsdam-Jena managed Land (LPJmL) model. LPJmL computes the dynamics of natural vegetation, annual crops and natural grasslands by considering carbon pools and fluxes, hydrological variables, and coupled photosynthesis and transpiration (Sitch et al., 2003; Gerten et al., 2004; Bondeau et al., 2007). The model has undergone major developments with respect to the hydrology, including a river routing and irrigation scheme (Rost et al., 2008), the management of dams and reservoirs (Biemans et al., 2011), and a five-soil-layer hydrology (Schaphoff et al., 2013). The representation of agricultural systems has also been improved by including bioenergy systems (tree and grass bioenergy plantations, jatropha, sugar cane; Beringer and Lucht, 2008; Lapola et al., 2009). An agricultural management module has been added, representing the combined influence of management practices on plant and stand development (e.g. fertiliser inputs, mechanisation, use of high-yielding varieties, weed and pest control, etc.; Fader et al., 2010), and better representation of sowing dates and multiple cropping systems (Waha et al., 2012, 2013). LPJmL is widely recognised as a state-of-the-art agro-ecosystem and hydrology model and has undergone the broadest possible range of validation efforts against experimental and observational data. In a recent intercomparison of global hydrological models and global gridded crop models for the assessment of future irrigation water availability, Elliot et al. (2014) indicated that LPJmL is unique in that it performs well in both categories. LPJmL is intensively used at the global and macro-regional scales in various research fields, particularly for questions related to future food security, land use change, and adaptation to climate change (Gerten et al., 2008; Rost et al., 2009; Lapola et al., 2010; Fader et al., 2010, 2013; Waha et al., 2013; Müller et al., 2014).

Since Mediterranean-specific crops have been lacking in LPJmL, we present here an extension that includes 10 new crop functional types that are especially important in the region. Most of these may be called "agricultural trees": nut trees, date palms, citrus trees, orchards, olive trees, grapes, cotton, potatoes, vegetables and fodder grasses. Their inclusion made it possible to account for ∼ 88 % of irrigated areas of the Mediterranean instead of ∼ 50 %.

The following section outlines the methodology applied, including the compilation of a new input data set with land use patterns which was needed for the validation and application of the model, the description of the modelling approach and parametrisation of the new crops, as well as the computation of irrigation requirements and soil carbon densities. The results section details exemplarily the performance of the model in simulating yields, soil carbon and irrigation water requirements. Finally, the paper is closed by a discussion on perspectives for future developments, potential applications and further refinements.

2 Methods

As a function of climatic conditions and agricultural management, LPJmL simulates, spatially explicitly and at a daily to yearly temporal resolution, growing periods (sowing and harvest dates), net and gross primary productivity, carbon sequestration in plants' compartments and soil, heterotrophic and autotrophic respiration, agricultural production, as well as a number of hydrological variables, such as runoff, soil evaporation, plant transpiration, plants' interception, percolation, infiltration, river discharge, irrigation water requirements, water stress and soil water content. Required inputs are (a) gridded, monthly climate variables (temperature, cloudiness interpolated to daily values and precipitation and rainy days converted through a weather generator in daily values); (b) atmospheric CO_2 concentrations; (c) gridded soil texture as described in Schaphoff et al. (2013); and (d) a gridded data set of land use patterns prescribing which crops are grown where and whether they are irrigated or rain-fed.

For the present study, we used climate inputs at 30 arcmin spatial resolution and global CO_2 concentrations derived from the CRU 3.10 data sets (Harris et al., 2014). The land use patterns for the crops in LPJmL had to be compiled from different sources, as explained in the following section. The model was spun up for 5000 years with dynamic natural vegetation in order to bring the carbon pools into equilibrium and additionally for 390 years with natural and agricultural vegetation. The spun-up simulations were followed by a transient run from 1901 to 2010 using the land use patterns described in the next section.

2.1 Land use patterns for use in LPJmL

LPJmL needs irrigated and rain-fed physical (as opposed to harvested) areas for each simulated crop. Physical and harvested areas differ through multiple cropping practices; that is, when one area is used twice in a year, the harvested area is twice as large as the physical area. For the present model development a new land use data set had to be compiled from different sources: Portmann et al. (2011), hereafter MIRCA, Monfreda et al. (2008), hereafter MON, Klein Goldewijk et al. (2011), hereafter HYDE, and Ramankutty et al. (2008), hereafter RAM.

The first step for the compilation of the land use data set was determining the harvested areas of all LPJmL classes, including the new Mediterranean crops, for the present time. For crops present in MIRCA, which differentiate between irrigated and rain-fed areas, all values in that study were used directly. For the missing crops, MON corresponding classes (see Table S1 in the Supplement) were compared at grid-cell level with MIRCA classes "other perennial" and "other annual", thereby splitting the harvested areas into the rain-fed and irrigated parts. This procedure was done for olives, non-citrus orchards, nut trees and vegetables. For the first three groups, MIRCA class "other perennial" was used for the grid-cell-specific splitting between rain-fed and irrigated areas. For vegetables, rain-fed and irrigated areas were derived through comparison with the "other annual" class.

Large inconsistences were found at the grid-cell level between MIRCA and MON, for example, cases where a single crop area in MON was larger than the sum of the rain-fed and irrigated corresponding "other" classes in MIRCA, and the absence or small extent of the class irrigated "other perennial” in areas that intuitively may be assumed to be irrigated, like in the case of orchards and olives in Egypt. The author of MIRCA (F. Portmann, personal communication, 2013) assumes that most of these inconsistences are due to scale, the grid-cell differences being potentially large but presenting a good agreement at the administrative level. Grasslands, representing meadows, were taken directly from RAM and assumed to always be rain-fed.

After deriving harvested areas for around the year 2000, the calculation followed the flowchart shown in Fig. S1 in the Supplement. Harvested areas were compared with cropland and grassland areas from RAM in order to exclude multiple cropping and derive physical cultivation areas. Decadal cropland data from HYDE were interpolated to derive annual values and then used for extrapolating the land use patterns of ∼ 2000 to the past, until 1700 (see below, Eqs. 1 to 5). Historical irrigation fractions were determined as explained in Fader et al. (2010).

Due to inconsistences between HYDE and the data set combining MIRCA, MON and RAM (hereafter MMR), proportionally changing cell fractions using the HYDE historical trend would have given an unrealistic overall trend of cropland areas. For this reason, crop-specific bias corrections had to be performed in between, as follows.

First, the global (g) area difference (D) was calculated:

$$D_{2000} = \mathrm{HYDE}_{g,2000} - \mathrm{MMR}_{g,2000}. \tag{1}$$

Bias correction of HYDE global values was performed by

$$\mathrm{HYDE}_{g,y,\mathrm{bias\_corrected}} = \mathrm{HYDE}_{g,y} - D_{2000}, \tag{2}$$

where y represents years from 1700 to 2000.

Cell (c) bias correction was done by

$$\mathrm{HYDEcorrected}, c, y = \frac{\mathrm{HYDE}c, y}{\mathrm{HYDE}g, y} \times \mathrm{HYDE}\, g, y, \mathrm{bias\_corrected}. \tag{3}$$

Proportional temporal change of MMR cell values was done from 2000 backwards by

$$\mathrm{MMR}y, c, \mathrm{proportional} = \frac{\mathrm{HYDEcorrected}, c, y}{\mathrm{HYDEcorrected}, c, y+1} \times \mathrm{MMRy}, c. \tag{4}$$

And final cell values ($\mathrm{LU}_{\mathrm{LPJmL}}$) were calculated by

$$\mathrm{LULPJmL} = \frac{\mathrm{HYDEcorrected}, g, y}{\mathrm{MIRCAproportional}, g, y} \times \mathrm{MMR}y, c, \mathrm{proportional}. \tag{5}$$

Cell fractions from 2001 to 2010 follow the trend between 1950 and 2000.

This procedure yields a gridded global data set at 30 arcmin spatial resolution of the cultivation areas of 24 crops from 1700 to 2010. Table 1 shows the resulting areas for each crop class of LPJmL. Expanding LPJmL for modelling Mediterranean crops made it possible to account for ∼ 88 % of irrigated areas of the Mediterranean instead of ∼ 50 %. For rain-fed areas, the improvement was from ∼ 21 to 73 %. The remaining areas are mostly fallow land and were included in the “others” model class which is parametrised as grasslands.

There is a general lack of information about the planting areas for agricultural trees at national and subnational level. Nevertheless, it was possible to make two comparisons. First, EUROSTAT offers information about olive tree areas at country level for eight countries of the northern Mediterranean. Our results are in good agreement with their numbers, with a mean absolute percent error of 26 % (MAPE, calculated as the sum of percentage differences between their values and our values, divided by their values, and finally multiplied by 1 over the sample size). Second, national harvested areas as reported by FAOSTAT for dates, olives, cotton seed, grapes and potatoes as an average of 2000 to 2009 could be compared with our data set. The agreement is high (MAPE $<$ 30 %) for all classes except for olives and dates (MAPE 47 and 46 %, respectively) where our data set has mainly smaller areas. This is due to the fact that MIRCA, RAM and MON have been compiled for the year 2000 and the FAO shows strongly an accelerated expansion of areas from 2000 to 2010, for example 54 % for olives in Morocco and 45 % for dates in Egypt and Turkey. Overall, the input data set compiled here has no better alternatives and appears to be broadly suitable for applications until newer versions of the land use data used as sources are released.

2.2 Implementation, calibration and parametrisation of Mediterranean agricultural trees and crops

Twelve crops were already present in LPJmL (temperate cereals, rice, tropical cereals, maize, temperate roots, tropical roots, pulses, rapeseed, soybeans, sunflower, sugar cane, others). In this study we included nut trees, date palms, citrus trees, orchards, olive trees, grapes, potatoes, cotton, vegetables and fodder grasses.

For each new crop, a representative species was selected for which the parameterisation was performed (see Table 2 for details on the parameters described in the following sentences). Potatoes were introduced as an annual crop following the approaches as described in Bondeau et al. (2007) for other annual crops. Potatoes are planted in early spring in cooler climates and late winter in warmer regions (FAO, 2008). In LPJmL they are sown each year in the areas indicated by the land use input, taking into account the seasonality of rainfall and temperature and the experience of farmers (see Waha et al., 2012). In the case of no water stress, leaf area index (LAI) development follows a prescribed curve (as in SWAT) with inflexion points according to the parameters shown in Table 2 (Phu_1/2, Lmax_1/2, Phusen), but LAI is

Table 1. Areas of LPJmL crops in the Mediterranean region. The stars indicate crops that are implemented in this study.

	Rain-fed		Irrigated		Total	
	10^6 ha	%	10^6 ha	%	10^6 ha	%
Temp. cer.	50.11	12.0	6.38	24.8	56.49	12.7
Maize	13.84	3.3	3.37	13.1	17.21	3.9
Fodder grass*	9.90	2.4	0.48	1.8	10.38	2.3
Trop. cer.	7.64	1.8	0.25	1.0	7.89	1.8
Pulses	6.03	1.4	0.68	2.6	6.71	1.5
Olives*	4.86	1.2	1.61	6.3	6.47	1.5
Vegetables*	4.24	1.0	1.60	6.2	5.84	1.3
Orchards*	4.27	1.0	1.26	4.9	5.53	1.2
Sunflower	4.40	1.1	0.43	1.7	4.82	1.1
Grapes*	4.09	1.0	0.59	2.3	4.68	1.1
Potatoes*	1.40	0.3	0.66	2.6	2.06	0.5
Cotton*	0.34	0.1	1.67	6.5	2.01	0.5
Nuts*	1.45	0.3	0.52	2.0	1.97	0.4
Temp. roots	1.17	0.3	0.74	2.9	1.91	0.4
Rapeseed	1.72	0.4	0.05	0.2	1.77	0.4
Groundnuts	1.56	0.4	0.11	0.4	1.67	0.4
Rice	0.14	0.0	0.88	3.4	1.02	0.2
Citrus*	0.12	0.0	0.86	3.3	0.98	0.2
Soybeans	0.63	0.2	0.17	0.7	0.80	0.2
Trop. roots	0.59	0.1	0.00	0.0	0.59	0.1
Date palm*	0.03	0.0	0.24	0.9	0.27	0.1
Sugar cane	0.16	0.0	0.09	0.3	0.24	0.1
Others	43.83	10.5	3.11	12.1	46.94	10.6
Grasslands	254.86	61.1	0.00	0.0	254.86	57.5
Total	417.36	100.0	25.74	100.0	443.10	100.0
Total without grasslands	162.50		25.74		188.25	
Crop area considered before/after development (%)	21/73		51/88		23/75	

reduced in the case of water stress by scaling it to the difference between atmospheric demand and water supply. Phenology and maturity are modelled after the heat unit theory: when the accumulated difference between daily temperatures and base temperature reaches a prescribed total growing degree amount (called hereafter PHU for potential heat units), then the potatoes are ripe and are harvested. Absorbed photosynthetically active radiation drives assimilation. Carbon allocation to different parts of the plant is a function of PHU development. The PHU parameter used depends on the mean temperature for spring varieties and on the sowing date for the winter/autumn varieties, and ranges from 1500 to 2400° Cd (with lower PHU in cooler climates).

Agricultural trees – including grapes and cotton which are modelled in the present study as small trees – are planted as samplings with 2.3 g carbon in sapwood and a LAI of 1.6 in the growing areas indicated by the land use input. Each agricultural tree has a country- and tree-specific planting density, and a tree-specific parameter determines the number of years that are needed for trees to grow before the first harvest. The latter parameter depends not only on the varieties used and on the biophysical situation, but also on management, especially on the usage of fertilisers and irrigation. There are insufficient quantitative data on this issue, and we therefore assumed this parameter to be 4 years for all agricultural trees. After these years, a plant-specific portion (HI, the "harvest ratio" or "harvest index") of the net primary productivity (NPP) of the tree is harvested every year. Thus, fruit growth is represented by a carbon accumulation that equals the multiplication of HI and NPP. An additional tree-specific parameter determines the replanting cycles of trees. Since there are no data available on this, we assumed that plantations are renewed (replanted) after 40 years. Most agricultural trees have chilling requirements; that is, they need a period of low temperatures before flowering. This is modelled using the parameter T_{lim} shown in Table 2. A 20-year running average of the coldest month maximum and minimum temperatures is compared with these values and defines the bioclimatic limits of each species. Hence, temperature warming above these limits would inhibit the establishment and survival of the perennial crops.

For deciduous trees, the active phase starts when the daily temperature is higher than the base temperature, and it is assumed that fruit growth occurs in the second half of the ac-

Table 2. Key parameters of agricultural trees and potatoes. **R**: representative tree/plant for parametrisation; **K_est**: tree density range; **HI**: harvest ratio/index; $\mathbf{T_b}$: base temperature; **GDD**: growing degree day requirements to grow full leaf coverage (in deciduous trees) or to reach ripeness of fruit (in evergreen trees); $\mathbf{T_{lim}}$: lower and upper coldest monthly mean temperature; $\mathbf{Ph_{opt}}$: lower and upper temperature optimum for photosynthesis; HE: maximal height of tree; **Phu_1/2:** fraction of potential heat units accumulated in the first (1) or second (2) inflexion point of the optimal leaf area curve; **Lmax_1/2**: fraction of maximal leaf area index accumulated in the first (1) or second (2) inflexion point of the optimal leaf area curve; **Phusen**: fraction of growing season at which senescence becomes the dominant process; **Lai_ha**: fraction of leaf area index still present at harvest; **PHU**: potential heat units for ripeness; **WCF**: water content factor for conversion from dry to fresh matter.

Crop	R	Seasonality	K_est (trees ha^{-1})	HI (frac)	T_b (°C)	GDD (acc. °C)	Ph_{opt} (° C)	T_{lim} (°C)	HE (m)	WCF (% of DM)
Citrus	Orange tree	Evergreen broadleaved	500–4600[g]	0.5[h]	18[a]	1000[i]	23 to 30[g]	−10 to 40[g]	10[j]	13[k]
Olive trees	Olive trees	Evergreen broadleaved	75–690[n,o]	0.45[f]	15[l]	1000[p]	15 to 30[n,m]	−10 to 15[n,m]	15[m]	30[q]
Date palm	Date palm	Evergreen broadleaved	100–920[r]	0.5[u]	14[s]	1700[u]	25 to 35[s]	−10 to 40[s]	20[s]	70[s,t]
Orchards	Apple tree	Deciduous broadleaved	325–2990[aa]	0.49[v]	7[a]	400[x]	15 to 25[a]	−15 to 15[z]	13[y]	16[k]
Nut trees	Almond tree	Deciduous broadleaved	100-920[ac]	0.6[w]	7[ab]	300[ad]	20 to 25[ab]	−10 to 15[ab]	10[ae]	90[af]
Grapes	Vine plants	Deciduous broadleaved	2000–15 000[ak]	0.6[al]	10[ai]	300[ah]	17 to 20[ag]	10 to 15[ag]	2[aj]	20[k]
Cotton	Cotton plants	Deciduous broadleaved	20 000–184 000[aq]	0.19[am]	15[ao]	300[ao]	16 to 22[ao]	−10 to 40[ao]	3[ap]	91[an]

Crop	R	LAI curve parameters (frac)						T_b	PHU	Ph_{opt}	WCF
		Phu_1	Lmax_1	Phu_2	Lmax_2	Phusen	Lai_ha	(°C)	(acc. °C)	(°C)	(% of DM)
Potatoes	Potatoes	0.15[a]	0.01[a]	0.5[a]	0.95[a]	0.9[a]	0.0[b]	0.0[c]	1500–2400[a]	16 to 25[a,d,e]	20[11]

[a] Neitsch et al. (2004) (SWAT model). For T_b of citrus, the T_b of poplar and oak was taken as a proxy. [b] Gordon et al. (1997). [c] Haverkort and MacKerron (1995) compiled different base temperatures in different studies and showed that a base temperature of 0.0 °C describes the tuberisation rate well in temperate zones. [d] FAO (2008). [e] Ku et al. (1977). [f] Morales Sierra (2012). [g] FAO (2013a). For T_{lim} of citrus, it was assumed that the rest can be induced by water deficit, not only by low temperatures. [h] Cannell (1985). [i] Based on FAO (2013a) information that indicates that citrus need 7 to 14 months from flowering to maturity. [j] Orwa et al. (2009). [k] Bastin and Henken (1997). [l] Aguilera et al. (2014). [m] California Rare Fruit Growers (1997). [n] FAO (2013b). [o] Roussos (2007). [p] Orlandi et al. (2014). [q] Kailis and Harris (2007). [r] Al-Khayri and Niblet (2012). [s] FAO (2002). [t] Elshibli (2009). [u] Large variations and lack of data lead to estimation of these parameters assuming relatively small, high-yielding varieties of palms, flowering around 1 month, developing fruits in around 4 months, with 1000 kg weight and yields of 500 kg per palm. [v] Zanotelli et al. (2013). [w] Toky et al. (1989). [x] Wünsche and Lakso (2000). [y] Parametrised as a standard apple tree and not as a dwarf. [z] Perry (2011). Apple, pear and cherry trees can survive lower winter temperatures, but other fruit trees (i.e. fig, peach and apricot trees) cannot. [aa] FAO (2011). [ab] Pontificia Universidad Católica de Chile (2008). [ac] Netafim (2013). [ad] Janick and Paull (2008). [ae] Duke (1983). [af] Alasalvar and Shahidi (2008). [ag] FAO (2013c). [ah] Meier (2001). [ai] Strik (2011). [aj] Ministry of agriculture, food and rural affairs (2013). [ak] Slovak Wine Academy Pezinok (2009). [al] Zamski and Schaffer (1996). [am] Sakin (2012). [an] Yan et al. (2007). [ao] Tsiros et al. (2009). [ap] Kiranga (2013). In wild conditions, cotton can be up to 5 m high, in crops, up to 1.5 m. [aq] Wright et al. (2004), Paytas and Tarrago (2011). Planting density varies largely.

tive phase of the year, i.e. when the phenological scalar (fraction of the maximum leaf coverage) is > 0.5 and before leaf senescence starts. Leaf senescence occurs when daily temperatures fall below the base temperature.

Following Sitch et al. (2003), evergreen trees are assumed to have constant leaf coverage and leaf longevities of more than 1 year. In this case, the accumulation of carbohydrates in the fruits occurs on days where temperature is above a tree-specific base temperature until a tree-specific threshold is reached (GDD).

Grass grows in the same areas of agricultural trees, except for cotton and grape plantations and orchards. For these three classes we assumed that grasses and weeds do not grow, thereby avoiding competition with the crops, implying that any ground cover is eradicated through some sort of weed control. This is the dominant practice in reality, although exceptions to this rule are gaining in importance.

Categories "vegetables" and "fodder grass" are modelled following the modelling approach of C3 grass described in Sitch et al. (2003). This is very appropriate for fodder grasses in the Mediterranean region since these are mainly alfalfa and clover. For vegetables, this parametrisation accounts for the very large physiological and allometric heterogeneity of vegetables, and also for multiple harvests per year, a fact that is well represented by a constant cover of the areas. Following the implementation of temperate herbaceous plant functional types (PFTs) in Sitch et al. (2003), the photosynthesis in vegetables and fodder grasses is assumed to be optimal between 10 and 30 °C. Vegetables and fodder grasses are harvested once their phenology is complete (i.e. the growing degree day accumulation determined by a parameter was reached) and the biomass increment is equal to or greater than $200\,\mathrm{g\,C\,m^{-2}}$ since the last harvest event. At that time, 50 % of the aboveground biomass is transferred to the harvest compartment. This assumption may be rather low for some vegetables such as lettuce, and rather high for others, such as beans. For the conversion from dry to fresh matter it was assumed that vegetables have an average water content of 40 %, which, again, is rather low for some cases, e.g. cucumbers, but rather high for e.g. garlic. The moisture content of fodder grass varies approximately between 10 and 75 %, depending on whether it is reported for hay, silage or fresh fodder. Here we represent fodder grass for hay production and assume thus a moisture content of 10 %.

The standard calibration process for agricultural management in LPJmL crops was extended in order to include agricultural trees. For annual crops this procedure consists in performing a set of runs with systematically modified management parameters representing the heterogeneity of fields, high-yielding varieties and the maximal achievable LAI (see more details in Fader et al., 2010). Similarly, 10 runs systematically modifying the tree- and country-specific plantation density parameter were performed to calibrate the management of agricultural tree plantations. Planting densities range from 25 to 230 % of the standard values, which were derived from literature research (see Table 2). For grapes the range was prescribed between 2000 and 15 000 vines per hectare. The tree density for each country was then chosen based on the best matching with reported FAO yields.

2.3 Irrigation water requirements and soil carbon

The computation of net and gross irrigation requirements (NIR and GIR, respectively; see below) in LPJmL is explained in detail in Rost et al. (2008) and Rohwer et al. (2006). The functioning of soil decomposition, soil biochemistry and soil hydrology, including soil organic carbon (SOC), is explained in Schaphoff et al. (2013) and Sitch et al. (2003). In the following paragraphs a short and simplified summary of these procedures will be given.

Irrigation is triggered in irrigated areas when soil water content is lower than 90 % of the field capacity in the upper 50 cm of the soil (here "irrigated layer"). The plants' NIR is modelled in LPJmL as the amount of water that plants need, taking into account the water holding capacity of the irrigated layer and the relative soil moisture (Rost et al., 2008):

$$\mathrm{NIR}\left[\mathrm{mm\,d^{-1}}\right] = \min\left(\frac{1}{f_{\mathrm{Ril}}}\left(\frac{D}{\mathrm{Sy}} - w_{\mathrm{r}}\right), 1 - w_{\mathrm{il}}\right)\mathrm{WHC}, \qquad (6)$$

where D ($\mathrm{mm\,d^{-1}}$) is the atmospheric demand, which depends on potential evapotranspiration and canopy conductance. Sy ($\mathrm{mm\,d^{-1}}$) is the soil water supply, which equals a crop's specific maximum transpirational rate if the soil is saturated or declines linearly with soil moisture. f_{Ril} (fraction) is the proportion of roots in the irrigated layer. w_{il} (fraction) is the water content in the irrigated layer. w_{r} (fraction) is the water content weighted with the root density for the soil column. WHC (mm) is the field capacity of the irrigated layer (water holding capacity). GIR, also called water withdrawal or extraction, is obtained by dividing NIR by the project efficiencies (EP):

$$\mathrm{GIR}\left[\mathrm{mm\,d^{-1}}\right] = \frac{\mathrm{NIR}}{\mathrm{EP}}. \qquad (7)$$

EP is a country-specific parameter calculated for LPJmL by Rohwer et al. (2006) after the approach described in the FAO irrigation manual (Savva and Frenken, 2002). It takes into account reported data on conveyance efficiency (EC), field application efficiency (EA) and a management factor (MF):

$$\mathrm{EP}\ [0 \text{ to } < 1] = \mathrm{EC} \times \mathrm{EA} \times \mathrm{MF}. \qquad (8)$$

EA represents the water use efficiency in the fields and its increase from surface irrigation systems, via sprinkler systems, to drip irrigation systems. EC represents the water use efficiency in the distribution systems and is assumed to be linked to irrigation systems (lower for open channels than for pressurised pipelines). MF varies between 0.9 and 1 and is higher in pressurised and small-scale systems under the assumption that large-scale systems are more difficult to manage (see more details in Rohwer et al., 2006).

The soil column in LPJmL has five hydrologically and thermally active layers (20, 30, 50 cm, 1 and 1 m thickness) where roots have access to water. Infiltration depends on the soil water content of the first layer (water that does not infiltrate runs off), and percolation between the layers was simulated following the storage routine technique (see Schaphoff et al., 2013, for more details). Excess water over the saturation level is assumed to feed subsurface runoff. LPJmL has two soil carbon pools, with intermediate and fast turnover (0.001 and 0.03 rate of turnover per year at 10 °C). The maximum decomposition rate is reached around field capacity and decreases afterwards due to decreased soil oxygen content. A simple energy balance model is used for the thermal soil module. It includes a one-dimensional heat conduction equation, convection of latent heat, thawing and sensible heat (see Schaphoff et al., 2013, for more details).

3 Results

The performance of the improved LPJmL version was tested by simulating agricultural yields, irrigation water requirements and soil carbon density, and comparing the results to published observations.

3.1 Agricultural yields

Figure 1 shows LPJmL-simulated yields in metric tonnes fresh matter per hectare for the calibrated run for all new crops where FAOSTAT had data in the Mediterranean region, averaged for the period 2000–2009. LPJmL simulates all nuts, olives, fruits and potatoes in very good agreement with reported values, showing Willmott coefficients[1] of ≥ 0.6 in all cases. Only two cases with large planting areas and significant differences are visible, both in Turkey, for grapes and nut trees. The latter is due to the chosen representative tree for the parametrisation of this group (almonds), which does not represent the majority of nut plantations in Turkey. In 2010 almost 70 % of nut trees in Turkey were hazelnuts and only 3 % almonds (FAO, 2015a). The underestimation of grape yield in Turkey might be related to more than one factor, including the fact that the wine sector has been very dynamic in recent years there, with increases in production but decreases in area harvested (FAO, 2015a). FAO calculates yields by dividing national production by harvested area and calculates, thus, an increase in yields and a higher average over the years analysed. Our input data set shows a slight increase in grape areas with relative constant production; hence, we calculated a lower yield average over the years. Also, the general parametrisation for European grapes probably cannot represent the special character of local Turkish varieties that are well adapted to sandy soils and high altitudes.

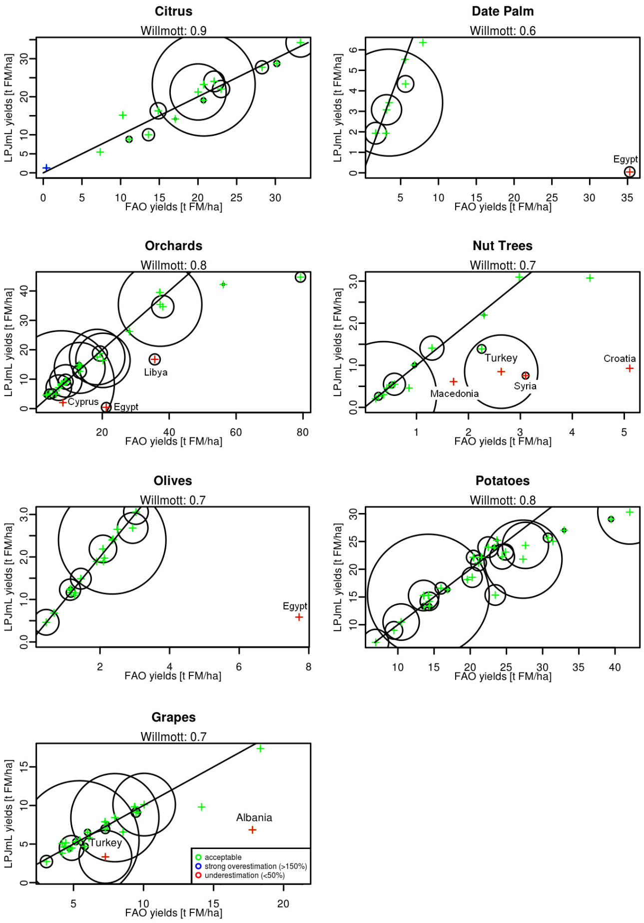

Figure 1. Scatter plot of LPJmL-simulated yields (averages over 2000–2009) versus reported yields from FAOSTAT for Mediterranean countries. The line represents the 1 : 1 line. FM stands for fresh matter. The radius of the bubbles indicates the relative size of the harvested area in the respective country.

Validating subnational patterns of yields is very difficult due to a general lack of data on this and important differences with other estimations in terms of scale, methods and time frames. However, we included in Fig. S2 a comparison with the yields from Monfreda et al. (2008) for the new crops where this study offers subnational data (note that their estimates are for the period of time around the year 2000 and at the administration level). LPJmL reproduces correctly a number of spatial patterns, such as some high-yielding regions: olives in Greece, vineyards in Israel, Lebanon, southern Spain, the Po Valley and the Italian regions of Emilia-Romagna and Lazio, potatoes in Turkey, Greece, Egypt,

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[1] The Willmott coefficient was developed by Willmott (1982) as a tool for testing model performance against independent data and is calculated by $1-\frac{\sum(p-o)^2}{\sum(/\mathrm{p}-\bar{o}/+/\mathrm{o}-\bar{\bar{o}}/)^2}$, where o is the independent data, p the LPJmL simulated data, and $\bar{o}$ denotes the mean of independent data.

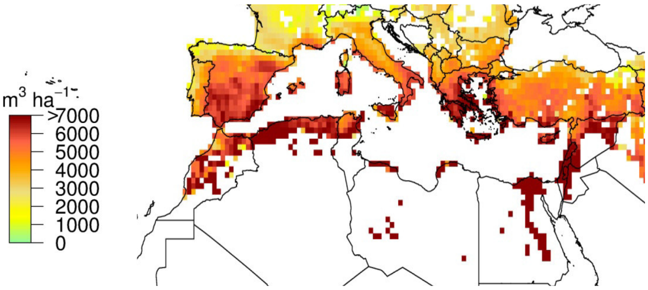

Figure 2. LPJmL-simulated net irrigation water requirements (NIR), as average over the period 2000–2009.

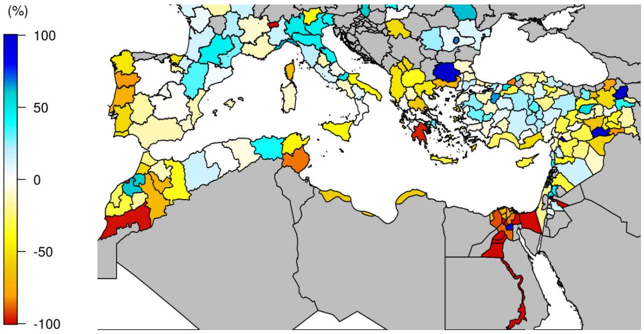

Figure 3. Comparison of irrigation consumptive water use from Siebert et al. (2010) and net irrigation water requirements computed in this study as a percentage of the Siebert et al. (2010) values. Negative (positive) values indicate higher (lower) values in their study.

Morocco, Israel, Lebanon and Algeria, as well as cotton yields in southern Spain, Greece, Turkey, Egypt, Israel and Lebanon. Also, some low-yielding zones are in good agreement, as is the case for potatoes in the Balkans, Portugal and Tunisia, olives in Morocco, Algeria and Tunisia, and cotton in Tunisia. However, a few patterns shown by Monfreda et al. (2008) are not shown in LPJmL simulations, including the north–south pattern of olives in Spain, the high-yielding zone of olives in southern Italy, and the grape and olive yields in Egypt. The first case is due to the extremely high management intensity in southern Spain which is not captured by the national calibration of planting densities (Scheidel and Krausmann, 2011). The latter case is originated by differences between the MON and MIRCA land use data sets that produce a lack of irrigated areas of grapes and olives in Egypt in our data set (see Sect. 2.2 for more details). The same is the case for the gaps in potatoes, e.g. in France. Overall there is a large agreement with no systematic differences between the spatial patterns shown by Monfreda et al. (2008) and the ones computed in the present study.

3.2 Irrigation water requirements

Figure 2 shows LPJmL-simulated NIR per hectare, which presents a clear north–south pattern that follows the climate-driven patterns of potential evapotranspiration. Konzmann et al. (2013) presented simulated irrigation requirements globally for around 10 crop functional types with a former version of the LPJmL model where tree plantations were represented as mowed grasslands. Their Fig. 1 shows a grid-cell pattern broadly similar to ours, but our more detailed representation of Mediterranean crops leads to higher values in various regions, including Algeria, Tunisia, Israel, Lebanon, Greece and the Iberian Peninsula. This is in good agreement with a general tendency of trees to absorb and transpire more water than grasslands (Belluscio, 2009).

Siebert et al. (2010) computed present irrigation consumptive water use for subnational administrative units by means of the GCWM model that compares well with our NIR estimates (Fig. 3). However, they estimated higher values in Egypt, Libya, Greece and Portugal, and lower values in the Po Valley and southern France. These differences are mainly linked to disparities in the land use data set used as inputs: Siebert et al. (2010) areas equipped for irrigation are larger than the ones used in the present study in the first group of countries, and smaller in the second group. The comparison in absolute terms (Fig. S3) shows a similar pattern but with additional high differences in the Spanish province of Andalucía. These differences may be linked to the model approach, for example, the difference in the crops considered (olives, orchards, and nuts are only considered in the present study by LPJmL), different methods to model evapotranspiration (Penman–Monteith versus Priestley–Taylor) and differences in growing periods (e.g. dynamic versus static sowing dates for annual crops). Since Andalucía is a region strongly characterised by horticulture, and taking into account that we parametrised vegetables as C3 grasses, it is worthwhile looking in more detail into this class, also because neither Siebert et al. (2010) nor the present study account for cultivation of vegetables in greenhouses. We computed independent irrigation water requirements of 2357 $m^3\ ha^{-1}$ based on the values presented in Table 2 from Gallardo and Thompson (2013) that concerns various vegetables and water melon grown in greenhouses. Based on the crop cycles described in their publication, we assumed the possibility of planting three types of vegetables per year using the same area (multiple cropping). Vegetables are planted on around 1.6 Mha in the Mediterranean region. This yields a total water consumption of 11.3 km^3. The present study computed 9.7 km^3, that is, a very similar value.

In total, the agricultural sector in the Mediterranean was simulated to withdraw approx. 223 km^3 of water per year for irrigation (average 2000–2009), with GIR being especially high in the Nile Delta, the eastern Mediterranean and in some Spanish regions (not shown). Our national GIR values are in good agreement with AQUASTAT data (FAO, 2015b) (Fig. 4, squares), with some differences. It is difficult to evaluate the quality of the AQUASTAT data. For example, the values of three countries with large differences from our estimates (Al-

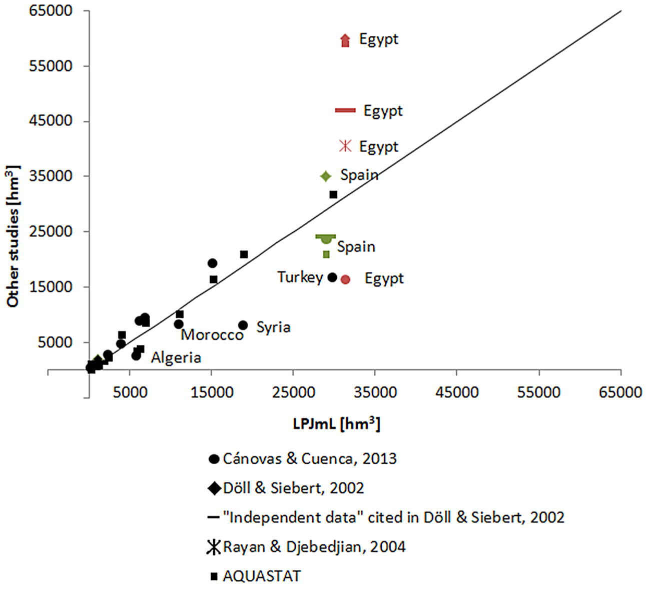

Figure 4. Scatter plot of LPJmL-simulated gross irrigation water requirements (hm^3, averages over 2000–2009) and the estimates presented by other studies. The line represents the 1 : 1 line. Egypt and Spain have been coloured in red and green, respectively, to visualise the disparities between different studies. (Note that Cánovas Cuenca, 2013, assumes a fixed requirement of 6176 $m^3\ ha^{-1}$.)

geria, Lebanon and Jordan) are in fact not reported data but modelled data. Assuming that the modelling was performed by the FAO's CROPWAT model, our estimates might be more accurate, since we perform a validated process-based calculation of transpiration instead of prescribing crop water coefficients. Another example of uncertainty is shown in the case of Egypt. In Fig. 4 (red symbols) it is evident that the estimates for Egypt vary largely; for example, Rayan and Djebedjian (2004) presented much lower estimates than AQUASTAT.

Döll and Siebert (2002) were probably the first authors who quantified irrigation water requirements at the global level while distinguishing two crop classes (rice and non-rice). Their Table 5 shows GIR for Egypt, Israel and Spain according to independent data and their calculations (using irrigation areas from 1995 and climate from 1961 to 1990). Despite the difference in the period of time analysed and the methodology, Fig. 4 shows that our results agree well for Israel and Spain for the independent data (from the water commissioner of Israel and the executive secretary of the International Commission of Irrigation and Drainage, respectively), while they found their values to be overestimated for both countries. For Egypt, independent data deliver 30 % higher GIR than our calculations and 27 % lower than the values of Döll and Siebert (2002). However, the reliability of the reported water use data cannot be established, especially in the case of Egypt, where these numbers are relevant for negotiations on water allocation treaties with upstream countries of the Nile River.

A report by Cánovas Cuenca (2013), quoting an unpublished paper by Cánovas and del Campo (2006), shows in its Table 17 irrigation water requirements for Mediterranean countries assuming that every hectare agriculture needs 6176 m^3 of water per year. Our analysis shows that while this number delivers a fair estimate of irrigation requirements for some northern Mediterranean countries, it strongly underestimates irrigation requirements of dry Mediterranean countries (Fig. 4, dots). This confirms that the environmental and climate diversity of the Mediterranean region requires spatially explicit modelling approaches.

To summarise, LPJmL computes Mediterranean irrigation water requirements in the range of former studies, even if comparisons are a challenge due to inconsistent model inputs, differences in modelling approaches, and due to the fact that to our best knowledge, this is the first study with a complete representation of Mediterranean crops.

3.3 Soil carbon density

As mentioned in the introduction, some assessments can only be performed with a model that includes natural and agricultural ecosystems with a fair detail in the hydrological cycle. This is the case for carbon sequestration by soils in a unit of area that has both natural and agricultural vegetation – a very important variable for the climate debate and the ecosystem service research domain.

Soils under forest, grasslands, and cropland show different carbon densities depending on climate, vegetation, soil structure, and management. Generally speaking, forests have higher proportions of soil organic carbon (SOC) compared to mowed grasslands, and they, in turn, have higher values compared to cropland planted with annual crops (Jobbágy and Jackson, 2000; Eclesia et al., 2012; Werth et al., 2005). Also, evergreen broadleaved forests and plantations have usually higher SOC than deciduous forests and plantations in semi-arid climates (Doblas-Miranda et al., 2013). Agricultural tree plantations have a lower tree density than forest, generally a regular distribution of trees that increase soil evaporation, and they are subject to removal of biomass (harvest). These factors lead to lower SOC values in tree plantations compared to forest. However, management of tree plantations, including irrigation input, planting density, presence or eradication of grass strips and mulching can strongly increase or decrease SOC. Putting all this information together and assuming that management and environmental factors are comparable, the SOC of agricultural tree plantations is expected to be generally higher than the SOC of mowed grasslands and generally lower than the SOC of natural forests and native grasslands. This is especially true for evergreen tree plantations and managed grasslands with high-frequency mowing. Hence, the implementation of agricultural trees in the LPJmL should produce higher SOC over the entire soil profile in

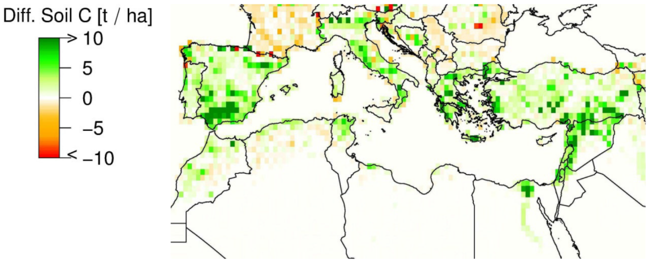

Figure 5. Difference in LPJmL-simulated soil organic carbon (average 2000–2009) before and after the implementation of agricultural trees described in this study. Negative (positive) values indicate that the development decreased (increased) soil organic content.

many Mediterranean areas. This is because before the implementation of agricultural trees, the areas corresponding to these agro-ecosystems were simulated as mowed grasslands.

As expected, Fig. 5 shows that implementing agricultural trees in LPJmL increased the carbon stock in soils in the whole Mediterranean except France. This exception is due to the fact that there are only two new implemented crops in France with significant areas: non-citrus orchards and grapes. Both are deciduous trees, with high soil evaporation at the beginning and end of the active period affecting carbon decomposition. Also, orchards have a relatively low planting density in France (1300 trees per hectare), which reduces shadow effects and litter input that, in turn, results in lower soil carbon compared to high-density mowed grass.

Validation of the new SOC patterns is very challenging since SOC measurements are spatially discontinuous as well as dependent on local conditions, sampling method and small-scale drainage conditions. Comparison with empirically based or process-based modelled SOC is also difficult due to differences in approaches, parameters, processes considered and issues of scale. Nevertheless, we compared our SOC estimates before (LPJmL$_{\mathrm{Old}}$) and after (LPJmL$_{\mathrm{New}}$) the implementation of agricultural trees with the organic carbon density from the HWSD database (Hiederer and Köchy, 2012). These data are produced by establishing functions between SOC and soil type, topography, climate variables and land use situation. For this comparison we calculated the difference of absolute differences ($/\mathrm{LPJmL}_{\mathrm{Old}} - \mathrm{HWSD}/ - /\mathrm{LPJmL}_{\mathrm{New}} - \mathrm{HWSD}/$, Fig. 6). Considering significant differences (results $<> 1\,\mathrm{t\,ha^{-1}}$), the number of grid cells with decreased differences to the HWSD estimates almost doubles the number of grid cells with increased differences (767 versus 460 grid cells). This means that the development presented in this study moved LPJmL's results for SOC closer to HWSD values.

As mentioned before, options for comparison with other SOC estimates are limited. The documentation of HWSD estimates (Hiederer and Köchy, 2012) offers an impressive effort in comparing their estimates with other assessments. They found large, spatially diverse differences from other estimates; some of them could be associated with differences in approaches. When comparing LPJmL results with HWSD estimates, it is necessary to bear in mind that HWSD offers a more detailed spatial scale and representation of processes linked to soil types, while LPJmL has a more detailed influence of land use history, seasonality of temperature and types of crops in SOC formation.

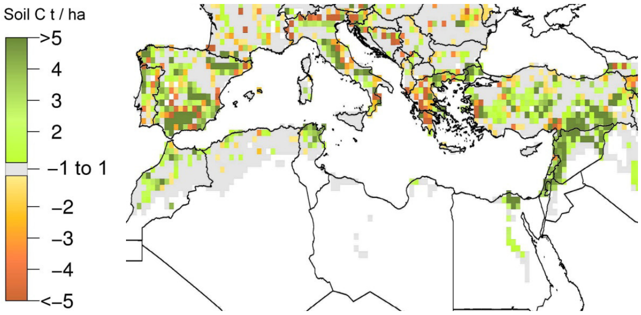

Figure 6. Difference between the HWSD soil carbon density and LPJmL-simulated soil carbon density before and after the model development presented here ($/\mathrm{LPJmL}_{\mathrm{Old}} - \mathrm{HWSD}/ - /\mathrm{LPJmL}_{\mathrm{New}} - \mathrm{HWSD}/$). Positive values indicate an improvement in simulation of soil carbon stock due to the implementation of Mediterranean crops described in the present study.

4 Discussion

4.1 Advances through consistent carbon–water–agriculture modelling

Environmental degradation, climate change, and population growth will put Mediterranean agriculture and natural ecosystems under pressure (IPCC, 2012; Kovats et al., 2014; Diffenbaugh and Giorgi, 2012; Skuras and Psaltopoulos, 2012; Doblas-Miranda et al., 2015). Timely and appropriate coping with the combination of these challenges will need collaboration between the Mediterranean countries and local communities in a number of issues, including advanced development of adaptation options, common plans on energy transition, environmental policy and best-practice rules in nature conservation and agricultural management. Collaboration will have to be designed in a framework that allows for taking into account of the larger European and global picture in terms of environmental change, dynamics of ecological systems, foreign investments and migration movements. This calls for new tools that are able to be applied at a large scale and can account for the interlinkages between agricultural systems, the carbon cycle, and water resources.

With the model development presented in the current study, LPJmL is now suitable for supporting Mediterranean decision makers. The inclusion of Mediterranean crops in LPJmL not only increased substantially the proportion of agricultural areas for which quantitative assessments are possible, but it also improved the potential for computation of irrigation requirements and soil carbon. The outcome is a model with a comprehensive representation of ecophysiological processes for all vegetation types (natural and agricultural) in a consistent and validated framework that produces estimates of carbon, agricultural and hydrological variables for the entire Mediterranean basin. As such, LPJmL is especially suitable for analyses of water issues. Taking into account the projected water scarcity due to climate change in the Mediterranean area, the continuously dropping groundwater tables due to overexploitation, and the projected increases in irrigation water demand (Fischer et al., 2007; Konzmann et al., 2013; Wada et al., 2010; Arnell, 2004), this constitutes a promising area for future model applications and further development. A first application of this model development was presented by Fader et al. (2015), pointing out that irrigation water needs of perennial crops in the Mediterranean region might increase significantly under climate change, and some countries may face constraints to meet the higher water demands.

4.2 Potential applications and perspective for further research

The inclusion of perennial crops in LPJmL presented in the current study opens up the possibility for a number of large-scale applications and research studies that cannot be performed with empirical and/or input-intensive agronomic models. These include assessments of climate change impacts on hydrological variables, agricultural production and carbon sequestration, as well as evaluation of consequences of land use change (including expansion of irrigated areas). Some of these applications could also be performed by land surface models, but LPJmL now has the advantage of considering perennial crops in detail, which allows more precise quantifications not only in the Mediterranean region, but also in other macro-regions where agriculture is partially dominated by tree crops, such as Australia, South Africa, Chile, western Argentina and California. Moreover, having a more accurate representation of perennial crops also allows studies on shifts in suitable growing areas for agricultural trees, diversity of diets, resilience of agricultural systems, needs for climate change adaptation and implications for food security, as well as assessments of ecosystem services provided by perennial cultures, for example habitat provision for avifauna.

Further improvements and refinements of LPJmL can be envisaged for applications in the Mediterranean area. We can divide these potential improvements into three groups, enumerated from least to most complex and work-intensive: (a) input-related, (b) parameter-related, and (c) inclusion of new processes.

The most important input-related improvement concerns national and subnational studies and is related to the need to increase the spatial resolution in all inputs used by LPJmL. The limited availability of climate data and scenarios in a higher spatial resolution for the whole basin as well as missing detailed flow direction maps, especially for North Africa, have constrained this refinement until now. Nevertheless, work on data interpolation and downscaling is ongoing to bring the model to the 15 arcmin resolution. Another input-related issue is the need for scenarios of future crop patterns as a consequence of climatic and socio-economic change. With climate change very likely affecting the potential growing areas of agricultural trees and their profitability, studies aiming at a future quantification of agricultural, biochemical and hydrological variables would profit from coupling between models like LPJmL and land use models.

Small-scale application aiming at comparing and analysing single crops may require parameter-related changes such as re-parametrisation allowing differentiation of harvesting times after uses and varieties (e.g. varieties of grapes, difference between table olives and olives for oil), grid-cell-specific planting densities and its differentiation between irrigated and rain-fed conditions, as well as crop-specific setting up of fruits, which at present depends on the phenological development but is not differentiated for different crops. For national-scale studies, re-parametrisation with different representative plants for the groups (e.g. using hazelnuts instead of almonds for nut trees in Turkey) is possible without any difficulty. For this group of improvements, data on management are essential, including harvesting times, post-harvest uses, planting densities, planted varieties, etc. Another benefit of more precise management information would be the possibility of differentiating parameters that are assumed to be static and equal for all plants in the present study, such as the number of years that a perennial plantation stays in production before being renewed and the period of time from the planting until the first harvest (see Sect. 2.2).

Some refinements in modelled processes should be undertaken for studies aiming at detecting year-to-year phenological changes or sub-yearly patterns of carbon allocation in agricultural trees. These may include improved representation of chilling requirements, for example, implementing the chilling units approach (Byrne and Bacon, 2015), the variable harvest index depending on the special conditions of the year, implementation of dwarf trees, and daily update of carbon partitioning. Also, including a more differentiated approach to agricultural management, such as discretising practices, typology and processes affected, may be necessary for assessments of climate change adaptation and soil carbon. Also connected to soil carbon, the inclusion of erosion and salinisation would be essential since this process plays an important role in the semi-arid, hilly and terraced landscapes of the Mediterranean area (García-Orenes et al., 2012; Poessen and Hooke, 1997).

Finally, the inclusion of horticulture in LPJmL opens the door to further large developments aiming at the assessment of alternative agro-ecosystem managements and their environmental performance. One clear example of this would be the link between agroforestry systems and biodiversity conservation.

Code availability and technicalities

LPJmL is written in the C programming language and is run mainly under UNIX-like systems. Inputs and outputs are in binary format. Depending on the size of the region analysed and on the desired spatial resolution, it may require a high-performing computational structure. The version used as the basis for the present development was 3.5.003 and the revision number 2133 from 17 May 2014.

The main site for downloads of different model versions can be found under https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml/versions.

There, downloads are free of charge and possible after registration. However, the latest model version that includes the agricultural module and the Mediterranean development is not available yet since the different working groups are still compiling a complete technical documentation and merging the last developments into one unique model version. Please contact the first author of this publication if you plan an application of the model and envisage longer-term scientific collaboration.

The Supplement related to this article is available online at doi:10.5194/gmd-8-3545-2015-supplement.

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References

Aguilera, F., Ruiz, L., Fornaciari, M., Romano, B., Galán, C., Oteros, J., Ben Dhiab, A., Msallem, M., and Orlandi, F.: Heat accumulation period in the Mediterranean region: phenological response of the olive in different climate areas (Spain, Italy and Tunisia), Int. J. Biometeorol., 58, 867–876, doi:10.1007/s00484-013-0666-7, 2014.

Alasalvar, C. and Shahidi, F. (Eds.): Tree Nuts: Composition, Phytochemicals, and Health Effects (Nutraceutical Science and Technology), Taylor and Francis, 340 pp., 2008.

Al-Khayri, J. M. and Niblett, C. L.: Envision of an international consortium for palm research, Emirates J. Food Agric., 24, 470–479, 2012.

Álvaro-Fuentes, J., Easter, M., Cantero-Martinez, C., and Paustian, K.: Modelling soil organic carbon stocks and their changes in the northeast of Spain, Eur. J. Soil Sci., 62, 685–695, doi:10.1111/j.1365-2389.2011.01390.x, 2011.

Arnell, N. W.: Climate change and global water resources: SRES emissions and socio-economic scenarios, Global Environ. Chang., 14, 31–52, doi:10.1016/j.gloenvcha.2003.10.006, 2004.

Baldocchi, D. and Wong, S.: An Assessment of Impacts of Future CO_2 and Climate on Agriculture, California Climate Change Center, 40 pp., 2006.

Bastin, S. and Henken, K.: Water Content of Fruits and Vegetables, University of Kentucky, available at: http://www2.ca.uky.edu/enri/pubs/enri129.pdf (last access: 13 March 2015), 1997.

Belluscio, A.: Planting trees can shift water flows, Nature News 7th November 2009, available at: http://www.nature.com/news/2009/091107/full/news.2009.1057.html (last access: 22 April 2015), 2009.

Beringer, T. and Lucht, W.: Nachhaltiges globales Bioenergiepotenzial, Commissioned expert study for the German Advisory Council on Global Change (WBGU) as a contribution to the flagship report World in Transition – Future Bioenergy and Sustainable Land Use, 2008.

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R. W. A., Heinke, J., von Bloh, W., and Gerten, D.: Impact of reservoirs on river discharge and irrigation water supply during the 20th century, Water Resour. Res., 47, W03509, doi:10.1029/2009WR008929, 2011.

Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., and Smith, B.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Global Change Biol., 13, 1–28, doi:10.1111/j.1365-2486.2006.01305.x, 2007.

Byrne, D. H. and Bacon, T.: Chilling accumulation: its importance and estimation, Dept. Of Horticultural Sciences, Texas AandM University, available at: http://aggie-horticulture.tamu.edu/stonefruit/chillacc.html (last access: 21 September 2015), 2015.

California Rare Fruit Growers: Olive, *Olea Europaea* L., available at: http://www.crfg.org/pubs/ff/olive.html (last access: 13 March 2015), 1997.

Cannell, M. G. R.: Dry matter partitioning in tree crops, in: Attributes of trees as crop plants, edited by: Cannell, M. G. R. and Jackson, J. E., Abbotts Ripton, Institute of Terrestrial Ecology, 160–193, available at: http://nora.nerc.ac.uk/7081/1/N007081CP.pdf (last access: 13 March 2015), 1985.

Cánovas Cuenca, J.: Report on water desalination status in the Mediterranean countries, Instituto Murciano de Investigación y Desarrollo Agrario y Alimentario, Consejería de Agricultura y Agua de la Región de Murcia, 308 pp., 2012.

Clothier, B., Hall, A. and Green, S.: Chapter 6, Horticulture, Adapting the horticultural and vegetable industries to climate change, available at: http://www.climatecloud.co.nz/CloudLibrary/2012-33-CC-Impacts-Adaptation_SLMACC-Chapter6.pdf (last access: 20 March 2015), 2012.

Diffenbaugh, N. S. and Giorgi, F.: Climate change hotspots in the CMIP5 global climate model ensemble, Climatic Change, 114, 813–822, doi:10.1007/s10584-012-0570-x, 2012.

Doblas-Miranda, E., Martínez-Vilalta, J., Lloret, F., Álvarez, A., Ávila, A., Bonet, F., Brotons, L., Castro, J., Curiel, J., Díaz, M., Ferrandis, P., García-Hurtado, E., Iriondo, J., Keenan, T., Latron, J., Llusià, J., Loepfe, L., Mayol, M., Moré, G., Moya, D., Peñuelas, J., Pons, X., Poyatos, R., Sardans, J., Sus, O., Vallejo, V., Vayreda, J., and Retana, J.: Reassessing global change research priorities in Mediterranean terrestrial ecosystems: how far have we come and where do we go from here?, Global Ecol. Biogeogr., 24, 25–43, doi:10.1111/geb.12224, 2015.

Doblas-Miranda, E., Rovira, P., Brotons, L., Martínez-Vilalta, J., Retana, J., Pla, M., and Vayreda, J.: Soil carbon stocks and their variability across the forests, shrublands and grasslands of peninsular Spain, Biogeosciences, 10, 8353–8361, doi:10.5194/bg-10-8353-2013, 2013.

Döll, P. and Siebert, S.: Global modeling of irrigation water requirements, Water Resour. Res., 38, 1037, doi:10.1029/2001WR000355, 2002.

Duke, J. A.: Handbook of energy crops, Purdue University, Center for New Crops and Plant Products, available at: http://www.hort.purdue.edu/newcrop/duke_energy/refa-f.html (last access: 13 March 2015), 1983.

Eclesia, R. P., Jobbagy, E. G., Jackson, R. B., Biganzoli, F., and Piñeiro, G.: Shifts in soil organic carbon for plantation and pasture establishment in native forests and grasslands of South America, Global Change Biol., 18, 3237–3251, doi:10.1111/j.1365-2486.2012.02761.x, 2012.

Elliott J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B. M., Folberth, C., Foster, I., Gosling, S. N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A. C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., and Wisser, D.: Constraints and potentials of future irrigation water availability on agricultural production under climate change, Proc. Natl. Acad. Sci., 111 , 3239–3244, doi:10.1073/pnas.1222474110, 2014.

Elshibli, S.: Genetic Diversity and Adaptation of Date Palm (*Phoenix dactylifera* L.), PhD Thesis University of Helsinki, 2009.

Fader, M., Rost, S., Müller, C., Bondeau, A., and Gerten, D.: Virtual water content of temperate cereals and maize: Present and potential future patterns, J. Hydrol., 384, 218–231, doi:10.1016/j.jhydrol.2009.12.011, 2010.

Fader, M., Gerten, D., Krause, M., Lucht, W., and Cramer, W.: Spatial decoupling of agricultural production and consumption: quantifying dependence of countries on food imports due to domestic land and water constraints, Environ. Res. Lett., 8, 014046, doi:10.1088/1748-9326/8/1/014046, 2013.

Fader, M., Shi, S., von Bloh, W., Bondeau, A., and Cramer, W.: Mediterranean irrigation under climate change: more efficient irrigation needed to compensate increases in irrigation water requirements, Hydrol. Earth Syst. Sci. Discuss., 12, 8459–8504, doi:10.5194/hessd-12-8459-2015, 2015.

FAO: Cultivation of Potatoes, available at: http://www.fao.org/potato-2008/en/potato/cultivation.html (last access: 13 March 2015), 2008.

FAO: Crop Water Information: Citrus, available at: http://www.fao.org/nr/water/cropinfo_citrus.html (last access: 13 March 2015), 2013a.

FAO: Crop Water Information: Olive, available at: http://www.fao.org/nr/water/cropinfo_olive.html, (last access: 13 March 2015), 2013b.

FAO: Crop Water Information: Grape, available at: http://www.fao.org/nr/water/cropinfo_grape.html (last access: 13 March 2015), 2013c.

FAO: Date palm cultivation, FAO Plant production and protection paper 156, Rev. 1, edited and compiled by: Zaid, A., available at: http://www.fao.org/docrep/006/y4360e/y4360e00.HTM (last access: 13 March 2015), 2002.

FAO: Tree crops, Guidelines for estimating area data, Statistics division, available at: http://www.fao.org/fileadmin/templates/ess/ess_test_folder/documents/Production_trade/definitions/Tree_crops_guidelines_for_estaimating_area.doc (last access: 13 March 2015), 2011.

FAO: FAOSTAT, available at: http://faostat.fao.org/site/567/default.aspx#ancor (last access: 1 July 2014), 2015a.

FAO: AQUASTAT, available at: http://www.fao.org/nr/water/aquastat/main/index.stm, (last access: 1 July 2014), 2015b.

Fischer, G., Tubiello, F. N., van Velthuizen, H., and Wiberg, D. A.: Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. Technol. Forecast. Soc., 74, 1083–1107, doi:10.1016/j.techfore.2006.05.021, 2007.

Gallardo, M. and Thompson, R. B.: Water requirements and irrigation management in Mediterranean greenhouses: the case of the southeast coast of Spain, in: Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean Climate Areas, edited by: FAO-AGP and ISHS-CMPC, FAO, Rome, Italy, 109–136, 2013.

Garcia de Cortázar-Atauri, I.: Adaptation du modèle STICS à la vigne (*Vitis vinifera* L.): utilisation dans le cadre d'une étude d'impact du changement climatique à l'échelle de la France, PhD thesis ENSAM, 292 pp., 2006.

García-Orenes, F., Roldán, A., Mataix-Solera, J., Cerda, A., Campoy, M., Arcenegui, V., and Caravaca, F.: Soil structural stability and erosion rates influenced by agricultural management practices in a semi-arid Mediterranean agro-ecosystem, Soil Use Manage., 28, 571–579, doi:10.1111/j.1475-2743.2012.00451.x, 2012.

Gerik, T., Williams, J., Francis, L., Greiner, J., Magre, M., Meinardus, A., Steglich, E., and Taylor, R.: EPIC-Environmental Policy Integrated Climate Model, User's Manual Version 0810, 2014.

Gerten, D., Luo, Y., Le Maire, G., Parton, W. J., Keough, C., Weng, E., Beier, C., Ciais, P., Cramer, W., Dukes, J. S., Sowerby, A., Hanson, P. J., Knapp, A., Linder, S., Nepstad, D., and Rustad, L.: Modelled effects of precipitation, on ecosystem carbon and water dynamics in different climatic zones, Global Change Biol., 14, 1–15, doi:10.1111/j.1365-2486.2008.01651.x, 2008.

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., and Sitch, S.: Terrestrial vegetation and water balance – hydrological evaluation of a dynamic global vegetation model, J. Hydrol., 286, 249–270, doi:10.1016/j.jhydrol.2003.09.029, 2004.

Gordon, R., Brown, D. M., and Dixon, M. A.: Estimating potato leaf area index for specific cultivars, Potato Res., 40, 251–266, doi:10.1007/BF02358007, 1997.

Gutierrez, A. P., Ponti, L., Ellis, C. K., and d'Oultremont, T.: Analysis of climate effects on agricultural systems: A report to the Governor of California, 43 pp., available at: http://www.climatechange.ca.gov/climate_action_team/reports/index.html (last access: 20 March 2015), 2006.

Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, Int. J. Climatol., 34, 623–642, doi:10.1002/joc.3711, 2014.

Haverkort, A. J. and MacKerron, D. K. L. (Eds.): Potato ecology and modelling of crops under conditions limiting growth, Kluwer Academic Publishers, The Netherlands, 1995.

Hervieu, B.: Agriculture: a strategic sector in the Mediterranean area, CIHEAM analytic note No. 18, 2006.

Hiederer, R. and Köchy, M.: Global Soil Organic Carbon Estimates and the Harmonized World Soil Database, EUR Scientific and Technical Research series – ISSN 1831-9424 (online), doi:10.2788/13267, 2012.

Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., Chenu, K., van Oosterom, E. J., Snow, V., Murphy, C., Moore, A. D., Brown, H., Whish, J. P. M., Verrall, S., Fainges, J., Bell, L. W., Peake, A. S., Poulton, P. L., Hochman, Z., Thorburn, P. J., Gaydon, D. S., Dalgliesh, N. P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F. Y., Wang, E., Hammer, G. L., Robertson, M. J., Dimes, J. P., Whitbread, A. M., Hunt, J. van Rees, H., McClelland, T., Carberry, P. S., Hargreaves, J. N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., and Keating, B. A.: APSIM – Evolution towards a new generation of agricultural systems simulation, Environ. Model. Softw., 62, 327–350, doi:10.1016/j.envsoft.2014.07.009, 2014.

IIASA/FAO: Global Agro-ecological Zones (GAEZ v3.0), IIASA, Laxenburg, Austria and FAO, 2012.

IPCC: Summary for Policymakers, in: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, , A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 3–21, 2012.

Janick, J. and Paull, R. E. (Eds.): Encyclopedia of Fruit and Nuts, Purdue University, USA, CAB International, 972 pp., 2008.

Jobbagy, E. G. and Jackson, R. B.: The vertical distribution of soil organic carbon and its relation to climate and vegetation, Ecol. Appl., 10, 423–436, 2000.

Kailis, S. and Harris, D.: Producing Table Olives, CSIRO Publishing, Collingwood, 2007.

Kiranga, N. A.: Morpho-argro-physio-karyotypic characterization of wild cotton (*Gossypium* spp.), Germplasm from selected counties in Kenya, available at: http://ir-library.ku.ac.ke/bitstream/handle/123456789/9050/NjagiAnthonyKiranga.pdf?sequence=1 (last access: 13 March 2015), 2013.

Klein Goldewijk, K., Beusen, A., de Vos, M., and van Drecht, G.: The HYDE 3.1 spatially explicit database of human induced land use change over the past 12,000 years, Global Ecol. Biogeogr., 20, 73–86, doi:10.1111/j.1466-8238.2010.00587.x, 2011.

Konzmann, M., Gerten, G., and Heinke, J.: Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model, Hydrol. Sci. J., 58, 88–105, doi:10.1080/02626667.2013.746495, 2013.

Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F.: Europe, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part B: Regional Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Barros, V. R., Field, C. B., Dokken, D. J., Mastrandrea, M. D., Mach, K. J., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R., and White, L. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1267–1326, 2014.

Kroes, J. G. and van Dam, J. C.: Reference Manual SWAP version 3.0.3. Alterra-report 773 3, Alterra, Green World Research, Wageningen, 211 pp., 2003.

Ku, S,-B., Edwards, G. E., and Tanner, C. B.: Effects of light, carbon dioxide, and temperature on photosynthesis, oxygen inhibition of photosynthesis, and transpiration in *Solanum tuberosum*, Plant Physiol., 59, 868–872, 1977.

Lapola, D. M., Priess, J. A., and Bondeau, A.: Modeling the land requirements and potential productivity of sugarcane and jatropha in Brazil and India using the LPJmL dynamic global vegetation model, Biomass Bioenergy, 33, 1087–95, doi:10.1016/j.biombioe.2009.04.005, 2009.

Lavorel, S., Canadell, J., Rambal, S., and Terradas, J.: Mediterranean terrestrial ecosystems: Research priorities on global change effects, Global Ecol. Biogeogr. Lett., 7, 157–166, doi:10.1046/j.1466-822X.1998.00277.x, 1998.

Lionello, P., Malanotte-Rizzoli, P., Boscolo, R., Alpert, P., Artale, V., Li, L., Luterbacher, J., May, W., Trigo, R., Tsimplis, M., Ulbrich, U., and Xoplaki, E.: The Mediterranean Climate: An Overview of the Main Characteristics and Issues, in: Mediterranean Climate Variability, edited by: Lionello, P., Malanotte-Rizzoli, P., and Boscolo, R., Developments in Earth and Environmental Sciences, 4, 1–26, 2006.

Lobell, D. B., Nicholas Cahill, K., and Field, C. B.: Historical effects of temperature and precipitation on California crop yields, Climatic Change, 81, 187–203, doi:10.1007/s10584-006-9141-3, 2007.

Lobianco, A. and Esposti, R.: The regional model for Mediterranean agriculture. IDEMA research project paper, available at: https://lobianco.org/antonello/_media/academic:pubs:idema_deliverable17.pdf, (last access: 21 September 2015), 2006.

Marsal, J. and Stöckle, C. O.: Use of CropSyst as a decision support system for scheduling regulated deficit irrigation in a pear orchard, Irrigation Sci., 30, 139–147, doi:10.1007/s00271-011-0273-5, 2012.

Marsal, J., Girona, J., Casadesus, J., López, G., and Stöckle, C. O.: Crop coefficient (K_c) for apple: comparison between measurements by a weighing lysimeter and prediction by CropSyst, Irrigation Sci., 31, 455–463, doi:10.1007/s00271-012-0323-7, 2013.

Marsal, J., Johnson, S., Casadesus, J., López, G., Girona, J., and Stöckle, C.: Fraction of canopy intercepted radiation relates differently with crop coefficient depending on the season and the fruit tree species, Agr. Forest Meteorol., 184, 1–11, doi:10.1016/j.agrformet.2013.08.008, 2014.

Meier, U.: Growth stages of mono-and dicotyledonous plants, BBCH Monograph, Federal Biological Research Centre for Agriculture and Forestry, Blackwell Wissenschafts-Verlag, 622 pp., 2001.

Ministry of Agriculture, Food and Rural Affairs: Wine grape production outside traditional areas in Ontario, available at: http://www.omafra.gov.on.ca/english/crops/facts/info_grapeprod.htm (last access: 13 March 2015), 2013.

Monfreda, C., Ramankutty, N., and Foley, J. A.: Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000, Global Biogeochem. Cy., 22, GB1022, doi:10.1029/2007GB002947, 2008.

Morales Sierra, A.: A model of productivity for olive orchards, MSc Thesis Plant Production Systems, Wageningen University, 2012.

Moriondo, M., Ferrise, R., Trombi, G., Brilli, L., Dibari, C., and Bindi, M.: Modelling olive trees and grapevines in a changing climate. Environ. Model. Softw., 72, 387–401, doi:10.1016/j.envsoft.2014.12.016, 2015.

Müller, C., Waha, K., Bondeau, A., and Heinke, J.: Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development, Global Change Biol., 20, 2505–2517, doi:10.1111/gcb.12586, 2014.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R., and Williams, J. R.: Assessment Tool, Input/output file documentation, Version 2005, Grassland, Soil and Water Research Laboratory, Temple, Texas, available at: http://swat.tamu.edu/media/1291/swat2005io.pdf (last access: 13 March 2015), 2004.

Nesme, T., Brisson, N., Lescourret, F., Bellon, S., Crété, X., Plénet, D., and Habib, R.: Epistics: A dynamic model to generate nitrogen fertilisation and irrigation schedules in apple orchards, with special attention to qualitative evaluation of the model, Agr. Syst., 90, 202–225, doi:10.1016/j.agsy.2005.12.006, 2006.

Netafim: Irrigation, Almond best practices, available at: https://www.netafim.com/crop/almond/best-practice (last access: 13 March 2015), 2013.

Orlandi, F., Garcia-Mozo, H., Ben Dhiab, A., Galán, C., Msallem, M., and Fornaciari, M.: Olive tree phenology and climate variations in the Mediterranean area over the last two decades, Theor. Appl. Climatol., 115, 207–218, doi:10.1007/s00704-013-0892-2, 2014.

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., and Anthony, S.: Agroforestree Database: a tree reference and selection guide version 4.0, World Agroforestry Centre, Kenya, 2009.

Paytas, M. and Tarrago, J.: Cotton genotypes performance under rainfed and irrigated conditions in two regions of northern Argentina, in: World Cotton Research Conference-5, edited by: Kranthi, K. R., Venugopalan, M. V., Balasubramanya, R. H., Kranthi, S., Singh, S., and Blaise, S.: Mumbai, India, 7-11 November 2011, 309–311, Excel India Publishers, New Delhi, 2011.

Perry, L.: Cold Climate Fruit Trees, University of Vermont Extension Department of Plant and Soil Science, available at: http://perrysperennials.info/articles/coldfruit.html (last access: 13 March 2015), 2011.

Pontificia Universidad Católica de Chile: El Almendro, available at: https://climafrutal.wordpress.com/el-almendro/ (last access: 13 March 2015), 2008.

Portmann, F., Siebert, S., and Döll, P.: MIRCA 2000 – Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling, Global Biogeochem. Cy., 24, GB1011, doi:10.1029/2008GB003435, 2011.

Ramankutty, N., Evan, A. T., Monfreda, C., and Foley, J. A.: Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000, Global Biogeochem. Cy., 22, GB1003, doi:10.1029/2007GB002952, 2008.

Rayan, M. A. and Djebedjian, B.: Egypt's Water Demand, Supply and Management Policies. International Water Demand Management Conference, 30 May–3 June 2004, Dead Sea – Jordan, available at: http://www.academia.edu/2085529/Egypt_sWater_Demand_Supply_and_Management_Policies (last access: 13 March 2015), 2004.

Rohwer, J., Gerten, D., and Lucht, W.: Development of functional irrigation types for improved global crop modelling, PIK Report 104, Potsdam, 98 pp., 2006.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S.: Agricultural green and blue water consumption and its influence on the global water system, Water Resour. Res., 44, W09405, doi:10.1029/2007WR006331, 2008.

Roussos, P. A.: Training and Pruning Olives. Proceedings of the MGS Symposium: Dry Gardening – Philosophy and Practice, Agricultural University of Athens, Greece, available at: http://www.mediterraneangardensociety.org/olives.html (last access: 13 March 2015), 2007.

Sakin, E.: Net primary productivity of southeast Anatolia Region (SAR) in Turkey, Int. J. Agr. Biol., 14, 617–620, 2012.

Savva, A. P. and Frenken, K.: Monitoring the Technical and Financial Performance of an Irrigation Scheme, Irrigation Manual Module, 14, 58 pp., 2002.

Scarascia-Mugnozza, G., Oswald, H., Piussi, P., and Radoglou, K.: Forests of the Mediterranean region: gaps in knowledge and research needs, Forest Ecol. Manage., 132, 97–109, doi:10.1016/S0378-1127(00)00383-2, 2000.

Schaphoff, S., Heyder, U., Ostberg, S., Gerten, D., Heinke, J., and Lucht, W.: Contribution of permafrost soils to the global carbon budget, Environ. Res. Lett., 8, 014026, doi:10.1088/1748-9326/8/1/014026, 2013.

Scheidel, A. and Krausmann, F.: Diet, trade and land use: a socio-ecological analysis of the transformation of the olive oil system, Land Use Policy, 28, 47–56, doi:10.1016/j.landusepol.2010.04.008, 2011.

Schröter, D., Cramer, W., Leemans, R., Prentice, I. C., Araújo, M. B., Arnell, N. W., Bondeau, A., Bugmann, H., Carter, T. R., Garcia, C. A., de la Vega-Leinert, A. C., Erhard, M., Ewert, F., Glendining, M., House, J. I., Kankaanpää, S., Klein, R. J. T., Lavorel, S., Lindner, M., Metzger, M. J., Meyer, J., Mitchell, T. D., Reginster, I., Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes M. T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., and Zierl, B.: Ecosystem service supply and vulnerability to global change in Europe, Science, 310, 1333–1337, doi:10.1126/science.1115233, 2005.

Siebert, S. and Döll, P.: The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops, Frankfurt Hydrology Paper 07, Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, 2008.

Siebert, S. and Döll, P.: Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation, J. Hydrol., 384, 198–217, doi:10.1016/j.jhydrol.2009.07.031, 2010.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., and Portmann, F. T.: Groundwater use for irrigation – a global inventory, Hydrol. Earth Syst. Sci., 14, 1863–1880, doi:10.5194/hess-14-1863-2010, 2010.

Sitch, S., Smith, B., Prentice, C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K. and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Global Change Biol., 9, 161–185, doi:10.1046/j.1365-2486.2003.00569.x, 2003.

Skuras, D. and Psaltopoulos, D.: A broad overview of the main problems derived from climate change that will affect agricultural production in the Mediterranean area, in: Building Resilience for Adaptation to Climate Change in the Agriculture Sector, edited by: Meybeck, A., Lankoski, J., Redfern, S., Azzu, N., and Gitz, V., Proceedings of a Joint FAO/OECD Workshop 23–24 April 2012.

Slowak Wine Academy Pezinok: Viticulture and viniculture, Study material, Elementary Seminar, Module 1, European Comission, Leonardo Davinci Transfer of Innovation Programm, 50 pp., available at: http://svapezinok.sk/files/gallery/20130103172711_WEB_SVA%20Zakladny%20seminar_EN_01.pdf (last access: 13 March 2015), 2009.

Sperling, O.: Water Relations in Date Palm Trees – a Combined Approach using Water, Plant, and Atmospheric Data, Ph.D. Thesis, Ben-Gurion University, 2013.

Strik, B. C.: Growing Table Grapes, EC 1639, Oregon State University, Extension Service, http://smallfarms.oregonstate.edu/sites/default/files/publications/growing_table_grapes_ec1639_may_2011.pdf (last access: 13 March 2015), 2011.

Toky, O. M., Kumar, P., and Kumar, P.: Structure and function of traditional agroforestry systems in the western Himalaya. I. Biomass and productivity, Agroforest. Syst., 9, 47–70, doi:10.1007/BF00120155, 1989.

Tsiros, E., Domenikiotis, C., and Dalezios, N. R.: Assessment of cotton phenological stages using agroclimatic indices: An innovative approach, It. J. Agrometeorol., 2009, 50–55, 2009.

Valdés-Gómez, H., Celette, F., García De Cortázar-Atauri, I., Jara-Rojas, F., and Gary, C.: Modelling soil water content and grapevine growth and development with the STICS crop-soil model under two different water management strategies, J. Int. Scie Vigne Vin, 43, 13–28, 2009.

Verner, D.: Adaptation to a Changing Climate in the Arab Countries: A Case for Adaptation Governance and Leadership in Building Climate Resilience, The World Bank, Washington, DC, 2012.

Villalobos, F. J., Testi, L., Orgaz, F., García-Tejera, O., Lopez-Bernal, A., González-Dugo, M. V., Ballester-Lurbe, C., Castel, J. R., Alarcón-Cabañero, J. J., Nicolás-Nicolás, E., Girona, J., Marsal, J., and Fereres, E.: Modelling canopy conductance and transpiration of fruit trees in Mediterranean areas: a simplified approach, Agr. Forest Meteorol., 171–172, 93–103, doi:10.1016/j.agrformet.2012.11.010, 2013.

Wada, Y., Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., and Bierkens, M. F. P.: Global depletion of groundwater resources, Geophys. Res. Lett., 37, L20402, doi:10.1029/2010GL044571, 2010.

Waha, K., van Bussel, L. G. J., Müller, C., and Bondeau, A.: Climate-driven simulation of global crop sowing dates, Global Ecol. Biogeogr., 12, 247–259, doi:10.1111/j.1466-8238.2011.00678.x, 2012.

Waha, K., Müller, C., Bondeau, A., Dietrich, J. P., Kurukulasuriya, P., Heinke, J., and Lotze-Campen, H.: Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa, Global Environ. Chang., 23, 130–143, doi:10.1016/j.gloenvcha.2012.11.001, 2013.

Werth, M., Brauckmann, H.-J., Broll, G., and Schreiber, K.-F.: Analysis and simulation of soil organic-carbon stocks in grassland ecosystems in SW Germany, J. Plant Nutr. Soil Sci., 168, 472–482, doi:10.1002/jpln.200421704, 2005.

Willmott, C. J.: Some comments on the evaluation of model performance, Bulletin American Meteorological Society, 1309–1313, 1982.

World Bank: Population Growth (Annual %), World Development Indicators, Washington, DC, available at: http://data.worldbank.org/indicator/SP.POP.GROW, last access: 1 December 2013.

Wright, S., Hutmacher, B., Shrestha, A., Banuelos, G., Keeley, M., Delgado, R., and Elam, S.: Double Row and Conventional Cotton in Tulare County, California, in: New directions for a diverse planet, edited by: Fischer, R. A., Proceedings of the 4th International Crop Science Congress, Brisbane, Australia, 26 September–1 October 2004, available at: http://www.regional.org.au/au/asa/2004/poster/2/7/4/1774_wrightsd.htm (last access: 13 March 2015), 2014.

Wünsche, J. N. and Lakso, A. N.: Apple Tree Physiology–Implications for Orchard and Tree Management. Presented at the 43rd Annual IDFTA Conference, 6–9 February 2000, Napier, New Zealand, available at: http://virtualorchard.net/IDFTA/cft/2000/july/cftjuly2000p82.pdf (last access: 13 March 2015), 2000.

Yan, H., Cao, M., Liu, J., and Tao, B.: Potential and sustainability for carbon sequestration with improved soil management in agricultural soils of China. Agriculture, Ecosyst. Environ., 121, 325–335, doi:10.1016/j.agee.2006.11.008, 2007.

Zamski, E. and Schaffer, A. A.: Photoassimilate distribution in plants and crops: source-sink relationships, Marcel Dekker, Inc., New York, 33 pp., 1996.

Zanotelli, D., Montagnani, L., Manca, G., and Tagliavini, M.: Net primary productivity, allocation pattern and carbon use efficiency in an apple orchard assessed by integrating eddy covariance, biometric and continuous soil chamber measurements, Biogeosciences, 10, 3089–3108, doi:10.5194/bg-10-3089-2013, 2013.

Zdruli, P.: Land resources of the Mediterranean: Status, pressures, trends and impacts of future regional development, Land Degrad. Dev., 25, 373–384, doi:10.1002/ldr.2150, 2014.