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Extension of the CAPRI model with an irrigation sub-module

María BLANCO
Peter WITZKE
Ignacio PÉREZ DOMÍNGUEZ
Guna SALPUTRA
Pilar MARTÍNEZ

Editors: Ignacio PÉREZ DOMÍNGUEZ
Guna SALPUTRA

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Joint
Research
Centre

Contact information
Address: Edificio Expo, c/Inca Garcilaso, 3, E-41092 Seville (Spain)
E-mail: jrc-ipts-secretariat@ec.europa.eu
Tel.: +34 954488318

JRC Science Hub
https://ec.europa.eu/jrc

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Abstract:
The study enables the CAPRI model to make simulations of the potential impact of climate change and water availability on agricultural production, as well as is looking at the sustainable use of water and the implementation of water-related policies including water pricing. To investigate the role of irrigation as adaptation strategy to climate change, we define a set of simulation scenarios that account for the likely effects on water price, crop yields, water availability and irrigation efficiency.

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Executive summary

Policy context

In Europe, irrigation water use by agriculture has been identified as one of the major sustainable management options in the implementation of the Water Framework Directive. Future water scenarios may imply changes in both water use intensity and the water demand from different sectors and, therefore, may imply changes both in irrigation water demand and irrigation water availability. Moreover, irrigation can be considered an adaptation strategy to climate change. At its own initiative the IPTS in collaboration with the CAPRI model network **developed a water component for the CAPRI model which allows to add the water dimension to the analysis of agricultural and climate change policies**. In particular, we introduce an analysis of the interplay between irrigation water and food production which is lacking in most previous studies. This report covers an analysis of scenarios and documentation concerning the implementation of the module on irrigation and livestock water use.

Key conclusions

Water stress is a key element when performing impact assessments of agricultural policy options. Moreover, **economic assessments of the impacts of climate change on agriculture need to include farm- and market-level adjustments in order not to overestimate the negative effects of climate change**. Water availability is already a limiting factor for agricultural production in many EU regions, and in the future the pressures on water are expected to increase. Climate change may add additional risks and jeopardise the sustainable use of this vital resource.

Irrigation plays an important role as adaptation strategy, partially offsetting the negative effects on crop productivity of limited water availability. However, if irrigation expansion implies using more water, this increase in irrigation water use will place additional stress on water resources. Therefore, **improved irrigation efficiency and, in general, improved water use efficiency, can reduce climate risks and make agriculture less vulnerable to changing climate conditions.** Measures stimulating efficient water use are crucial to move towards a climate-resilient sustainable agriculture.

In terms of modelling efforts it may also be concluded that **much is missed when neglecting irrigation from a global perspective**, such that an extension of this work in order to represent irrigation in non-EU regions would be a natural step. However, that will also require adjusting to more serious data problems at the global level.

The current implementation still leaves ample room for future improvements. The **availability of data is critical for the quality of the final results**. In the development phase, *ad hoc* assumptions or second choice data have been used to address data gaps. For example, while data on total irrigable and irrigated area per region are provided by EUROSTAT, crop-specific irrigated area is provided for only a selected group of crops. Moreover, regional data are provided only a limited number of crops and for one single year (2010). As a result, crop-specific irrigated areas are based on a single year dataset. These assumptions may be amended or replaced as new data become available.

Main findings

Including irrigation in the supply module of CAPRI implies: (1) making a distinction between irrigable land and non-irrigable land, and fit this to the existing land balance in CAPRI, (2) making a distinction between rain fed area and irrigated area for all potential irrigable activities in the CAPRI model, (3) entering crop-specific irrigation water use as a specific input, (4) estimating input–output coefficients for all irrigated activities.Data on area equipped for irrigation (irrigable area) and area irrigated at least once a year (irrigated area) are available in EUROSTAT, as assessed in the Farm Structure Survey. For supply regions in CAPRI for which no irrigation data are provided in EUROSTAT, data on irrigation shares from the Food and Agriculture Organization of the United Nations have been used. To account for irrigation in land balances, arable land is split into irrigable land and rain fed land. The current implementation of input-output coefficients and costs for irrigated activities is based on assumptions about the cost differentials between irrigated and rain fed activities. Data on water availability, withdrawal and use come from EUROSTAT and European Commission datasets. Simulations are performed at NUTS 2 regional level.

Scenario analysis with the CAPRI water module include a baseline in year 2030, two water pricing and three climate change related scenarios. Overall, an **additional price for irrigation water will have significant negative impacts on irrigation shares**. For example as shown in Figure 1, reduction in irrigated areas is concentrated mainly in Southern and Eastern Europe. The decrease in irrigated areas for cereals and oilseeds will be compensated by an increase in rain fed areas for these crops. Nevertheless, effects on production differ across crops, as they are driven by two opposite forces: (1) decrease in the relative profitability of irrigated crops compared with rainfed crops and (2) the increased prices of agricultural outputs due to higher production costs, which stimulate production. The effects of increased irrigation efficiency included in scenario W2 lead to a smaller decrease in irrigated area and a larger decrease of total water use.

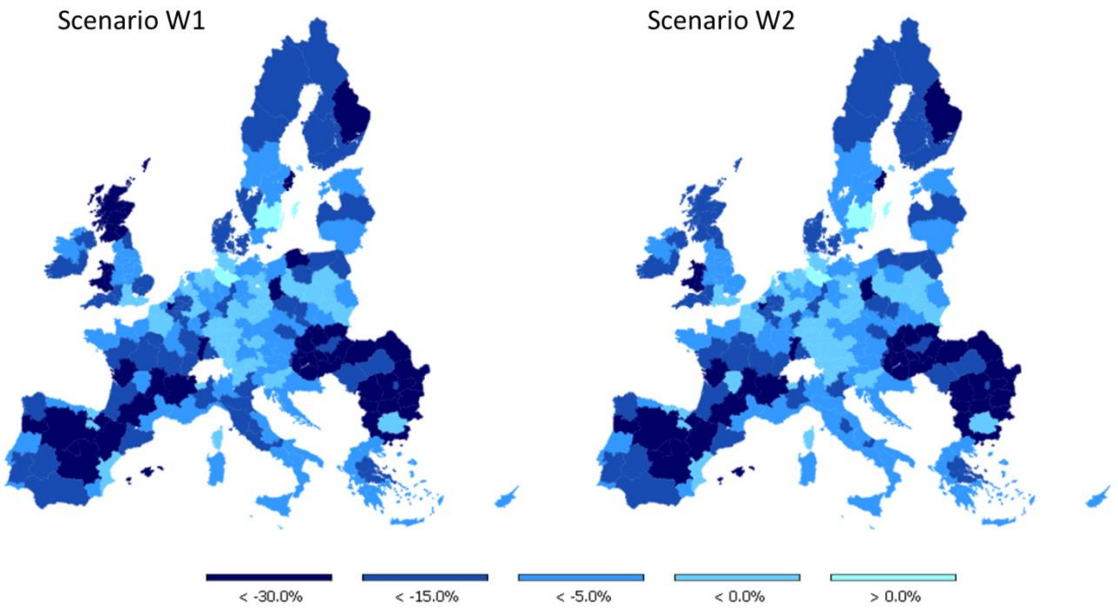

Figure 1. Percentage change from baseline in total irrigated land for the water pricing scenarios (W1: increase of 5 Eurocents per cubic meter / W2: W1 plus irrigation efficiency increase of 0.1% per annum)

With respect to **impacts of climate change, although yield effects strongly differ across products and regions, the overall effect is negative, driving up producer prices both globally and at EU level** (Figure 2). This leads to mixed results on crop production, but to particularly severe effects in the case of grain maize. The findings of this study are in line with previous studies analysing a similar scenario. Within the EU, differential effects for rain fed and irrigated crops can be analysed. Overall, yield effects are more negative for rain fed than for irrigated activities, but their shares change endogenously. As a result, climate change induces significant substitution effects between irrigated and rain fed areas.

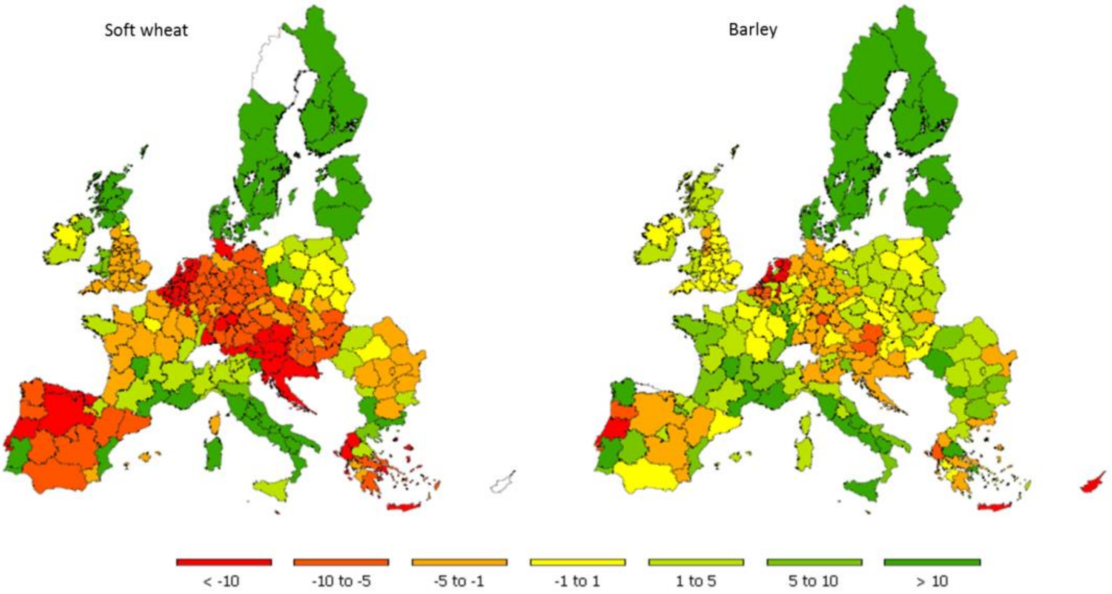

Figure 2. Production changes under a climate change scenario in 2030 (% changes vs. the baseline).

Related and future JRC work

The CAPRI water module presented here could be further developed in three dimensions, improvement of the water database; inclusion of water use balances at the EU level to take into account competition between agricultural and non-agricultural water uses in a more detailed way; and extension of the water module to non-EU Regions. Part of these activities are currently being explored as part of the Eenrgy-Agriculture-Water NEXUS project.

Quick guide

We expand the CAPRI model to include water use in agriculture by considering the existence of irrigated and rain fed crops as well as the water needs of livestock activities. This allows better reflecting on the impacts of water scarcity and climate change on agriculture. To do so information on irrigation area, costs and yields are needed. Such information is not available with the level of detail (both commodity and spatially) for which the CAPRI model works. Despite the limited availability of data, results show that there as water becomes scarcer or expensive agricultural income is reduced. However there is room for adaptation to climate change using irrigation technology improvements.The main objective of this study is to enable the Common Agricultural Policy Regional Impact Analysis (CAPRI) model to make simulations of the potential impact of climate change and water availability on agricultural production at the regional level, as well as looking at the sustainable use of water, the implementation of the Water Framework Directive and other water-related policies, including water pricing. As CAPRI is not a climate model but an agricultural sector model, effects of climate change on water availability have to be included in this context through the scenario assumptions, relying on external inputs, for example from other models. The advantage of the CAPRI model is that it allows the impacts of climate change on agriculture to be analysed both at the global level and at regional level within the EU.

In Europe, irrigation water use by agriculture has been identified as one of the major sustainable water management issues in the implementation of the Water Framework Directive (European Commission, 2000). Future water scenarios may imply changes in both water use intensity and the driving forces of water use and, therefore, may imply changes both in irrigation water demand and irrigation water availability. On the one hand, agricultural water resources are already under stress in many places and rising population and food demand will most likely exacerbate these pressures. On the other hand, agricultural water availability may be jeopardised by increasing water demands in the municipal, industrial and environmental sectors. To investigate the role of irrigation as adaptation strategy to climate change, we define a set of simulation scenarios that account for the likely effects on water price, crop yields, water availability and irrigation efficiency. This report covers an analysis of scenarios and documentation concerning the implementation of the module on irrigation and livestock water use.

Including irrigation in the supply module of CAPRI at the NUTS 2 level implies: (1) making a distinction between irrigable land (land equipped for irrigation) and non-irrigable land, and fit this to the existing land balance in CAPRI, (2) making a distinction between rainfed area and irrigated area for all potential irrigable activities in the CAPRI model, (3) entering crop-specific irrigation water use as a specific input, (4) estimating input–output coefficients for all irrigated activities.

Data on area equipped for irrigation (irrigable area) and area irrigated at least once a year (irrigated area) are available in EUROSTAT, as they are regularly assessed in the Farm Structure Survey (FSS) and reported at MS and NUTS 2 levels. For supply regions in CAPRI for which no irrigation data are provided in EUROSTAT (Western Balkans and Turkey), data on irrigation shares from the Food and Agriculture Organization of the United Nations (FAO) have been used. To account for irrigation in land balances, we split arable land into irrigable land and rainfed land. Irrigable land is the land equipped for irrigation and is, therefore, the maximum area that can be irrigated in a particular region at a given time. Irrigation water use is included as a crop-specific input. As this variable is not reported in official statistics, an estimation procedure based on theoretical water requirements, efficiency coefficients and actual irrigation water use by region have been applied.

The current implementation of input-output coefficients and costs for irrigated activities is based on assumptions about the cost differentials between irrigated and rainfed activities. No data are available on volumetric water prices in the irrigation sector for the base year period. Therefore, the simulation of water pricing systems should be interpreted as the introduction of additional prices for irrigation water. The additional cost is entered in the supply model through a specific equation accounting for irrigation water costs. Data on water availability, withdrawal and use come from JRC-IES datasets and simulations at NUTS 2 level. Water abstraction and use are reported for the irrigation, livestock, domestic, manufacturing and energy sectors. Livestock water use includes both drinking water and services water used in livestock farming (e.g. cleaning production units, washing animals, waste disposal).

Scenario analysis with the CAPRI water module captures a baseline, two water pricing and three climate change related scenarios. The baseline scenario for 2030 defines the reference situation and thus serves as a comparison point for the simulation scenarios defined in the previous section. The model provides simulated results both at the global level (around 40 trade blocks covering the globe) and at the regional level within Europe (around 280 NUTS 2 regions). New tables on irrigation have been added to the CAPRI graphical user interface (GUI) in order to show the disaggregation of crop activities into rainfed/irrigated variants.

1. Introduction

The main objective of this study is to enable the Common Agricultural Policy Regional Impact Analysis (CAPRI) model to make simulations of the potential impact of climate change and water availability on agricultural production at the regional level, as well as looking at the sustainable use of water, the implementation of the Water Framework Directive and other water-related policies, including water pricing. As CAPRI is not a climate model but an agricultural sector model, effects of climate change on water availability have to be included in this context through the scenario assumptions, relying on external inputs, for example from other models. The advantage of the CAPRI model is that it allows the impacts of climate change on agriculture to be analysed both at the global level and at regional level within the EU.

In Europe, irrigation water use by agriculture has been identified as one of the major sustainable water management issues in the implementation of the Water Framework Directive (European Commission, 2000). Agriculture accounts for an estimated 24 % of total water abstraction in Europe, although in parts of southern Europe this figure can reach up to 80 % (EEA, 2009). Moreover, unlike other sectors, for example energy production, the majority of the water abstracted for agriculture is consumed (by evaporation, transpiration and other losses) and is hence not returned to the water bodies (70 % according to the EEA).

Future water scenarios may imply changes in both water use intensity and the driving forces of water use and, therefore, may imply changes both in irrigation water demand and irrigation water availability. On the one hand, agricultural water resources are already under stress in many places and rising population and food demand will most likely exacerbate these pressures. On the other hand, agricultural water availability may be jeopardised by increasing water demands in the municipal, industrial and environmental sectors. To investigate the role of irrigation as adaptation strategy to climate change, we define a set of simulation scenarios that account for the likely effects on water price, crop yields, water availability and irrigation efficiency.

This report covers an analysis of scenarios and documentation concerning the implementation of the module on irrigation and livestock water use. The set-up of this report is as follows: the technical documentation of the water module is presented in Part 1. Part 2 describes the scenario analysis carried out under the project. Part 3 presents the modelling results. Part 4 gives an outlook for discussion on potential improvements on water modelling.

2. Methodology of modelling water in CAPRI

2.1 General CAPRI model structure

CAPRI is a partial equilibrium model for the agricultural sector developed for policy impact assessment of the Common Agricultural Policy and trade policies from global to regional scale with a focus on the EU (for a detailed description see Britz et al., 2014). It is a deterministic comparative partial static equilibrium model, solved by sequential iteration between supply and market modules:

- The market module is a static, deterministic, partial, spatial model with global coverage, depicting about 60 commodities of primary and secondary agricultural products and 40 trade blocks. It allows for simulating bilateral trade flows as well as bilateral and multilateral border protection instruments.
- The supply module consists of independent regional agricultural nonlinear programming models for EU-28 and candidate countries. Supply models depict farming decisions in detail at subnational level (Nomenclature of Units for Territorial Statistics (NUTS) 2 level or farm type level) by means of a mathematical programming approach, which offers a high degree of flexibility in capturing important interactions between production activities, the environment and the effects of agricultural and environmental policy measures.

2.2 CAPRI irrigation module for crops

Including irrigation in the supply module of CAPRI at the NUTS 2 level implies:

1. Making a distinction between irrigable land (land equipped for irrigation[1]) and non-irrigable land, and fit this to the existing land balance in CAPRI.
2. Making a distinction between rainfed area and irrigated area for all potential irrigable activities in the CAPRI model.
3. Entering crop-specific irrigation water use as a specific input.
4. Estimating input–output coefficients for all irrigated activities.

Figure 1 illustrates the modular structure: irrigable activities are split into rainfed and irrigated variants before solving the regional supply models and are aggregated again before solving the market model. The baseline has been calibrated with and without the water module, leading to different sets of model parameters.[2] For scenario analysis, the user can switch the water module on or off, activating the corresponding set of parameters.

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[1] We do not estimate areas that might be irrigated by moving mobile irrigation equipment from some areas to others, as the net effect on total irrigable land will be small and, in any case, difficult to assess.

[2] The baseline with the water module activated generates files with a suffix _w (e.g. sim_ini_w.gdx).

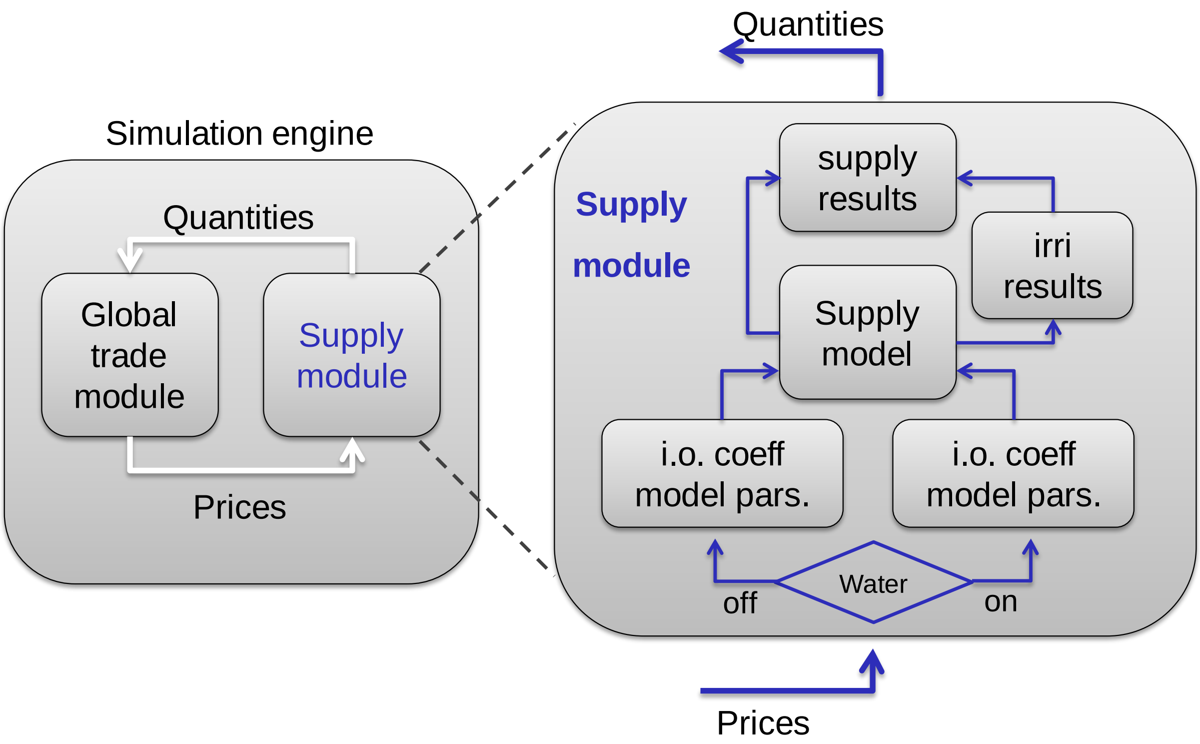

Figure 1 Schema of the integration of the water module in CAPRI.

Input–output coefficients for rainfed/irrigated variants are defined so as to match the aggregate activity coefficients. Data on irrigable and irrigated areas come from the Survey on Agricultural Production Methods (SAPM) 2010, which provides data at the NUTS 2 level and also includes a survey of irrigation methods. To account for irrigation in land balances, we differentiate irrigable land from total arable land. A new land constraint ensures that the irrigated area in each region does not exceed irrigable land.

$$IA_r = \sum_i X_{r,i} \leq PIA_{r,i}$$

where *r* accounts for region and *i* for irrigable activity, *IA* is regional irrigated area, *X* is the activity level and *PIA* is potentially irrigable area.

Irrigation water is included as a crop-specific input. As data on irrigation water use per crop and per region are not reported in official statistics, the actual irrigation water use is estimated for each crop and region based on theoretical crop water requirements, rainfed/irrigation shares, irrigation efficiency coefficients and actual irrigation water use by region (Blanco et al., 2012).

$$CWU_{r,i} = \frac{CNWU_{r,i}}{RAE_{r,i} \times RTE_r}$$

where *CWU* is crop water use, *CNWU* is crop net water use, *RAE* is regional irrigation application efficiency and *RTE* is regional irrigation transport efficiency.

At the regional level, total water availability for irrigation purposes is limited. This is expressed in the water supply balance, indicating that total water use by crops cannot exceed potential water availability:

$$RWU_r = \sum_i CWU_{r,i} * X_{r,i} \leq RWA_r$$

where *RWU* is regional irrigation water use and *RWA* is regional irrigation water availability.

As explained hereafter, several data sources have been used. Consolidation of these different and sometimes incomplete datasets is done using a standalone program (gams\water_database.gms). The consolidated water database is stored under results\capreg\water_res_%bas%.gdx.

2.2.1 Irrigable and non-irrigable activities

Crop production activities in the supply module of CAPRI are differentiated into irrigable and non-irrigable activities. In this context, irrigable activities are those for which an irrigated area has been reported in official statistics in at least one Member State (MS), whereas non-irrigable activities are those for which no irrigated area has been reported. Non-irrigable activities are handled in the supply module as described previously. In contrast, irrigable activities are split into rainfed and irrigated variants. If an activity is not irrigated in a particular region, only the rainfed variant exists in the database and model. Potential irrigable activities include most of the CAPRI crop activities, as shown in Table 1. Only the residual aggregates (other cereals, other oilseeds, other fodder) and the grass production activities are assumed non irrigable.

Table 1 Potential irrigable activities

Group	**Activity**	**Code**
Cereals	Soft wheat	SWHE
	Durum wheat	DWHE
	Rye and meslin	RYEM
	Barley	BARL
	Oats	OATS
	Grain maize	MAIZ
	Paddy rice	PARI
Oilseeds	Rape	RAPE
	Sunflower	SUNF
	Soya	SOYA
Other arable crops	Pulses	PULS
	Potatoes	POTA
	Sugar beet	SUGB
	Flax and hemp	TEXT
	Tobacco	TOBA
Vegetables and Permanent crops	Tomatoes	TOMA
	Other vegetables	OVEG
	Apples, pears and peaches	APPL
	Other fruits	OFRU
	Citrus fruits	CITR
	Table grapes	TAGR
	Olives for oil	OLIV
	Table olives	TABO
	Wine	TWIN
	Nurseries	NURS
	Flowers	FLOW
Fodder activities	Fodder maize	MAIF
	Fodder root crops	ROOF

Table 2 illustrates the activity-based approach followed in the CAPRI supply module. For irrigable activities, input/output coefficients must be specified for both the rainfed and the irrigated variants (the new components added in the irrigation module are highlighted in blue). While the position 'other irrigation costs (apart from water use)' has been included in the code, no data are available so far to allow these costs to be isolated from other cost components (e.g. repair costs or energy costs).

Table 2 Input–output coefficients for CAPRI activities – the example of soft wheat

SWHE (soft wheat production activity)	Input/output coefficient	Description	Unit
Outputs			
SWHE	3543.02	Soft wheat yield	kg/ha
STRA	2834.42	Straw yield	kg/ha
Inputs			
NITF	85.03	Organic and inorganic nitrogen applied	kg/ha
PHOF	36.86	Organic and inorganic phosphorus applied	kg/ha
POTF	72.28	Organic and inorganic potassium applied	kg/ha
WIRR		Irrigation water	m^3/ha
SEED	16.01	Seed input	Constant euro (2005)/ha
PLAP	15.38	Plant protection products	Constant euro (2005)/ha
REPA	34.25	Repair costs	Constant euro (2005)/ha
ENER	47.38	Energy costs	Constant euro (2005)/ha
IRRO		Other irrigation costs (apart from water use)	Constant euro (2005)/ha
INPO	25.48	Other inputs	Constant euro (2005)/ha
Income indicators			
TOOU	632.75	Value of total outputs	Current euro/ha
TOIN	337.15	Value of total inputs	Current euro/ha
GVAP	295.60	Gross value added at producer prices	Current euro/ha
PRME	156.90	CAP premiums	Current euro/ha
MGVA	452.50	Gross value added at producer prices plus premiums	Current euro/ha
Activity level and data relating to CAP			
LEVL	1393.43	Hectares cropped	1000 ha
IRSH		Irrigated area share	%
HSTY	2.29	Historic yield used to define CAP premiums	t/ha
SETR	2.86	Set aside rate	%

Source: CAPRI database, Spain example, base year data (average 2007–2009).

2.2.2 Irrigable and irrigated areas

Data on area equipped for irrigation (irrigable area) and area irrigated at least once a year (irrigated area) are available in EUROSTAT, as they are regularly assessed in the Farm Structure Survey (FSS) and reported at MS and NUTS 2 levels.

Irrigation data from EUROSTAT have been collected for years 2000, 2003, 2005, 2007 and 2010. However, apart from the year 2010, these datasets are incomplete at the NUTS 2 level and, therefore, of little use in the present study. As a result, the 2010 datasets are the main sources of data on irrigation areas. For 2010, irrigation data are available through the FSS and SAPM 2010. Crop-specific irrigated area is provided only for 10 selected crops: durum wheat, maize, potatoes, sugar beet, soya, sunflower, fodder plants, vines, fruit and berry orchards, and citrus fruit. Irrigation shares for the remaining crops are estimated so as to match total irrigated area in the region[3] and taking into account the following assumptions:

- Rice is always irrigated.
- Tiny irrigated areas are introduced for all existing crops (to allow for irrigation adoption in simulation scenarios).

For supply regions in CAPRI for which no irrigation data are provided in EUROSTAT (Western Balkans and Turkey), data on irrigation shares from the Food and Agriculture Organization of the United Nations (FAO) have been used.

The share of irrigation methods is derived from SAPM 2010, which includes a survey of irrigation methods and provides data at the NUTS 2 level. From this dataset, we calculated the area share covered by specific irrigation methods (surface irrigation, sprinkler irrigation and drop irrigation) in 2010. In the current implementation, we assume the share of each irrigation method in the CAPRI base year (three year average 2007–2009) matches the EUROSTAT figures for 2010. As there is no update of this dataset, it will be difficult to update the CAPRI database on this issue.

To account for irrigation in land balances, we split arable land into irrigable land and rainfed land. Irrigable land is the land equipped for irrigation and is, therefore, the maximum area that can be irrigated in a particular region at a given time. Hence, for each region with irrigation, we define a new constraint for irrigable land,[4] indicating that the total irrigated area in the region cannot exceed the total irrigable land.

The main variables for irrigation areas included in the consolidated database are presented in Table 3.

Table 3 Main CAPRI variables for irrigation areas (NUTS 2 level)

Topic	Variable	Unit	Code
Irrigation area	Total irrigable area	1 000 ha	IRRI
	Total irrigated area	1 000 ha	IRR2
	Irrigation share	%	IRSH
	Crop-specific irrigated area	1 000 ha	LEVi
	Crop-specific rainfed area	1 000 ha	LEVr
Irrigation method	Surface irrigation	%	IMSUR
	Sprinkler irrigation	%	IMSPR
	Drop irrigation	%	IMDRO

2.2.3 Estimation of input–output coefficients and costs for irrigated activities

Irrigation water use is included as a crop-specific input. As this variable is not reported in official statistics, an estimation procedure based on theoretical water requirements, efficiency coefficients and actual irrigation water use by region will be applied. The main variables used to model crop–water relationships in CAPRI are presented in Table 4.

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[3] The raw data are imported via CAPRI file dat\envind\fss_sapm2010_irrigation.gdx (besides NUTS 2 data; NUTS 3 data are also used when available). The consolidation with total irrigated area occurs in file gams\water_database.gms

[4] In file gams\supply_model.gms

Table 4 Main CAPRI variables for crop-water linkages

Topic	Variable	Unit	Code
Irrigation water	Crop net irrigation requirement	m^3/ha	CNIR
	Crop actual irrigation water use	m^3/ha	CAWU
	Gross irrigation water use	m^3/ha	WIRR
	Irrigation water application efficiency	%	IRWAE
	Irrigation water transport efficiency	%	IRWTE
Crop yield	Rainfed to irrigated yield ratio		YRATIO
	Actual crop yield	kg/ha	YIELD
	Rainfed crop yield	kg/ha	YLDr
	Irrigated crop yield	kg/ha	YLDi

Crop net irrigation requirement (CNIR) is the total volume of water needed by a certain crop, in addition to the rainfall, to achieve the potential yield[5] or maximum attainable yield under conditions of no stress. Crop actual irrigation water use (CAWU) can be equal to CNIR (full irrigation) or lower than CNIR (deficit irrigation). In other words, under water-limited conditions, CAWU will fall below CNIR and water stress will adversely affect crop growth. As a result, the actual crop yield (YIELD) might be lower than the potential crop yield. YIELD is reported in official statistics and makes up part of the CAPRI database. In order to define the technology variants for the irrigated activities so that they are consistent with crop–water relationships, we use the yield ratio YRATIO (potential yield/water limited yield), which is derived from biophysical simulations with the World Food Studies (WOFOST) model[6] (simulations for 10 major crops within the EU at the NUTS 2 level). Total production (crop area multiplied by crop yield) equals rainfed production plus irrigated production. The ratio of rainfed yield to irrigated yield equals the ratio of potential to water-limited yield. These two relationships allow the differentiation of rainfed and irrigated yields for the base year period.

Since data on irrigation water use per crop and per region are not reported in official statistics, CAWU is estimated for each irrigated region based on theoretical crop water requirements, rainfed/irrigation shares and crop yields (Blanco et al., 2013). Several approaches can be envisaged to estimate crop–water relationships, all of which are based on biophysical models:

1. The AquaCrop model – given its simplicity and robustness – could be chosen to estimate crop water requirements, potential yields (non-water-limited conditions) and rainfed yields (standard rainfed conditions). Alternatively, the CropWat model could be used to compute crop water requirements.
2. Another option would be to use the global dataset of monthly irrigated and rainfed crop areas around the year 2000 - MIRCA.[7] This dataset refers to the period 1998–2002 and is consistent with the irrigated area statistics of the AQUASTAT programme of FAO and to version 4.0.1 of the Global Map of Irrigation Areas.

The current code uses the first option. The CropWat model provides theoretical irrigation requirements, and has been used to compute net irrigation requirement by crop and

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[5] In agriculture *potential yield* is defined as the maximum yield a variety can achieve under no input restriction conditions.

[6] WOFOST model: http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/alterra/Facilities-Products/Software-and-models/WOFOST.htm

[7] MIRCA data available at http://www.uni-frankfurt.de/45218023/MIRCA

NUTS 2 region. The ratio of potential to water-limited yield comes from biophysical simulations with WOFOST (also at the NUTS 2 level). This is the best solution because the MIRCA data are not up to date (estimations are available only for the year 2000).

Several concepts of irrigation efficiency need to be used in order to proceed to gross irrigation water use by crop. In this report, we distinguish between water application efficiency (IRWAE) and water transport efficiency (IRWTE). IRWAE is the ratio of the volume of irrigation water evapotranspirated by the crop to the volume of water applied to the crop. This ratio depends on the irrigation method and management practices and can vary between 0 and 1. Using the indicative values for each irrigation method and for the estimated area share by irrigation method, we can compute the regional application efficiency per activity. IRWTE is the ratio of irrigation water used to irrigation water withdrawn. The transport efficiency mainly depends on irrigation infrastructure and water management of the canals, the soil type or permeability of the canal banks, and the condition of the canals.

Taken into account the irrigation water use efficiency, the gross irrigation water use (WIRR) can be calculated:

$$WIRR_{ri,wact} = \frac{CAWU_{ri,wact}}{IRWAE_{ri,wact} \times IRWTE_{ri}}$$

The shares of each irrigation method are used as weights to compute irrigation efficiencies at the NUTS 2 level. Data are processed in the program gams\water_database.gms and results are stored under parameter p_irriWeff (results\capreg\res_water_%bas%.gdx). Improvements to this approach would require additional biophysical data as well as data on water balances.

EU-wide statistics appear to be lacking in the area of irrigation costs. Water is included as a cost item in the European Farm Accounting Data Network (FADN), but this cost component includes only the cost of connection to a water delivery system and the costs of water consumption. Water application costs as well as irrigation investment costs are not reported separately in FADN. The cost of using irrigation equipment is recorded under 'current upkeep of machinery and equipment', 'motor fuels and lubricants' and 'electricity'. Capital cost is recorded under 'investment' and 'depreciation'. As production costs given by FADN are not broken down to the level of agricultural activities, CAPRI uses an econometric procedure to allocate farm input costs to particular agricultural activities (Jansson and Heckelei, 2011). In spite of the difficulties in individualising irrigation costs, FADN data will be used as much as possible for consistency with the input allocation model in CAPRI. Nevertheless, as available data on irrigation costs are very limited, additional data from national statistics should, ideally, be used to fill the gaps in EU-wide statistics.

Through the input allocation process, inputs such as feed, NPK (nitrogen, phosphorus and potassium) fertiliser, energy or plant protection costs are allocated to individual production activities in CAPRI. Several sources are combined in a statistical approach that ensures consistency with the Economic Accounts of Agriculture and other statistics on feed and fertiliser use, including the following: econometric estimates based on single farm data from the FADN; engineering information from the literature (e.g. requirement functions for animals or nutrient contents of crops); standard gross margins from EUROSTAT. The initial estimates for the input allocation based on FADN data cannot be updated in an automated way. Therefore, separating irrigation from the aggregated cost components would mean that proper allocation rules would have to be defined, the earlier estimation repeated and the input allocation procedure thoroughly reorganised.

The current implementation is based on assumptions about the cost differentials between irrigated and rainfed activities. More precisely, production costs for the average activity (composite of rainfed and irrigated variants) are not changed, so as to allow for a modular implementation of the water module, although cost allocation to rainfed and irrigated variants depends on yield differentials. As data on irrigation costs are very limited in EU-wide statistics, additional data (national statistics, expert data, literature, etc.) are required to further develop the cost allocation procedure. Water use costs are separated from other irrigation costs. A specific position wat_cost has been created to account for simulating water pricing scenarios. No data are available on volumetric water prices in the irrigation sector for the base year period. Therefore, the simulation of water pricing systems should be interpreted as the introduction of additional prices for irrigation water. The additional cost is entered in the supply model through a specific equation accounting for irrigation water costs.

2.2.4 Water availability issues

Data on water availability, withdrawal and use come from JRC-IES datasets and simulations at NUTS 2 level for 2006. Water abstraction and use are reported for the irrigation, livestock, domestic, manufacturing and energy sectors. Data on irrigation water use are also available through EUROSTAT for 2010 (SAPM 2010). However, this dataset is incomplete and a comparison with the JRC-IES data shows large disparities. Water availability constraints will be entered at regional level to express that regional irrigation water use (WUSE, WIRR) cannot exceed potential irrigation water availability (WAVA, WIRR). Regional irrigation water use (WUSE, WIRR) is computed by summation over all irrigated crops.

2.3 Livestock water use

2.3.1 Methodological approach

Livestock water use includes both drinking water and services water used in livestock farming (e.g. cleaning production units, washing animals, waste disposal). As described in the feasibility study (Blanco et al., 2012), the approach used to compute livestock water use is based on water use intensities. First, daily water requirements for each livestock category are taken from available data sources. Next, water use coefficients per head will be calculated by taking into account the length of the growing period. Finally, these coefficients are multiplied by the herd size given by CAPRI to compute total water use in the livestock sector. Several sources of data for livestock water use were identified (see Table 5). The daily water requirement (litres/head/day) varies significantly according to type of livestock, age and physiological conditions of the animal, environmental conditions and management.

Table 5 Data sources for livestock water use

Main Source	Information extracted
Van der Leeden (1990)	Information: water requirements for farm animals. Units used: gallons per day Factors considered: age, milk production, body weight Livestock type: cattle, dairy heifers, Jersey cows, Holstein cows, pigs, sheep, chickens Source: US Department of Agriculture
Lardy et al. (2008)	Information: estimated water intakes and water requirements for livestock Units used: gallons per head per day Factors considered: age, body weight, month and monthly average temperature Livestock type: lactating cows, dry cows, bred cows and heifers, bulls, growing cattle, finishing cattle, dairy cattle, sheep, swine Sources: Water Requirements for Beef Cattle (NRC, 2000); Dairy Reference Manual, Pennsylvania State University

Shroeder (2012)	Information: estimated water intakes and water requirements for dairy cattle Units used: gallons per day Factors considered: class of dairy cattle, milk yield, dry matter consumed, temperature Livestock type: lactating cows, dry cows, calves and heifers Sources: equation used according to the 2001 Nutrient Requirements of Dairy Cattle (NRC)
Ward and McKague(2007)	Information: estimated water intakes for livestock. Units used: litres per day Factors considered: animal category, weight Livestock type: milking cows, lactating cows, pigs, lactating sows, laying hens, sheep
Steinfeld et al. (2006)	Information: drinking water requirements for livestock Units used: litres per animal per day Factors considered: physiological condition, average weight, air temperature Livestock type: cattle, goat, sheep, chicken, swine
NRC (several years)	Information: daily water intake units used: litres per animal per day Factors considered: class of cattle, temperature and weight Livestock type: dairy cows, growing heifers, finishing cattle, lactating cows, pigs, poultry, sheep

The Water Encyclopedia (Van der Leeden, 1990) is a comprehensive data source for water resources issues. This dataset has been used to quantify livestock-specific water use intensities in Europe (Florke and Alcamo, 2004). The publications on 'Nutrient Requirements' by the National Research Council are also extensively cited (NRC, 1994, 2000, 2001, 2007, 2012). Mubareka et al. (2013) developed the livestock water requirement map series at JRC-IES, based on the FAO livestock density maps for 2005 (Robinson et al., 2007) and using the CAPRI database to account for herd sizes at the regional level. Water requirements per livestock type data were taken from the literature in order to compute water requirements for each livestock type on a daily basis. However, there is no explicit indication of which coefficients from the literature are used.

2.3.2 Drinking water requirements for livestock

In order to identify and select potential data for use in CAPRI, we compared the different datasets available following, as far as possible, the CAPRI livestock categories. It is generally recognised that the water intake of livestock comes from three sources: (1) water consumed voluntarily (drinking water); (2) water contained in feedstuffs; and (3) water formed within the body as a result of the metabolic oxidation of nutrients. Drinking water requirements depend upon a wide range of factors, such as type and size of animal, physiological state (lactating, pregnant or growing), type of diet, ambient temperature and water quality (palatability and salt content). As drinking water requirements are affected by many factors, it is not straightforward to list specific requirements with accuracy. Moreover, a comparison between different sources is challenging given that the coefficients were often estimated based on different assumptions. This is especially true for dairy cows whose water requirements depend on specific factors such as milk yield, weight, cow breed and dry matter intake. In this subsection, we compare drinking water coefficients from different sources – grouped by type of livestock – and we present the coefficients to be used in the supply module of CAPRI.

Dairy cows require large amounts of drinking water (see Table 6). Some major factors affecting water intake by dairy cattle are dry matter intake, milk production, dry matter content of the diet, temperature and environment, and sodium intake (NRC, 2001). Several authors have published formulas for estimating water requirements. NRC (2001) recommends the formula developed by Murphy et al. (1983) to estimate free water intake:

$$FWI = 15.99 + 1.58 \times DMI + 0.90 \times MY + 0.05 \times SI + 1.20 \times Tmin$$

where FWI is free water intake (kg/day), DMI is dry matter intake (kg/day), MY is milk yield (kg/day), SI is sodium intake (g/day) and $Tmin$ is minimum temperature (°C).

Table 6 Drinking water requirements of dairy cattle

Source	Category	Litres per day
Lardy et al. (2008)	Jersey cows (30 lbs milk/day)	53.94
	Guernsey cows (30 lbs milk/day)	56.40
	Ayrshire, Brown Swiss, and Holstein cows (30 lbs milk/day)	59.62
	Ayrshire, Brown Swiss and Holstein cows (50 lbs milk/day)	96.53
Shroeder 2012	Lactating cow (40 lbs milk/day)	83.13
	Lactating cow (60 lbs milk/day)	95.85
	Lactating cow (80 lbs milk/day)	108.49
	Lactating cow (100 lbs milk/day)	121.36
Ward and McKague (2007)	Dairy calves	9.0
	Dairy heifers	25.0
	Milking cows	115.0
	Dry cows	41.0
Initial value in CAPRI	Dairy cows production activity low yield	80.0
	Dairy cows production activity high yield	110.0

Table 7 Drinking water requirements of beef cattle

Source	Category	Litres per day
NRC (2000)	Growing heifers, steers, and bulls (weight 182 kg)	22.0
	Growing heifers, steers, and bulls (weight 273 kg)	29.5
	Growing heifers, steers, and bulls (weight 364 kg)	34.8
	Finishing cattle (weight 273 kg)	32.9
	Finishing cattle (weight 364 kg)	40.5
	Finishing cattle (weight 454 kg)	47.7
	Wintering pregnant cows (weight 409 kg)	36.7
	Lactating cows (weight 409 kg)	64.0
	Mature bulls (weight 636 kg)	44.3
	Mature bulls (weight 727 kg)	47.7
Initial value in CAPRI	Male adult fattening activity low final weight	40.5
	Male adult fattening activity high final weight	47.7
	Heifers fattening activity low final weight	29.5
	Heifers fattening activity high final weight	34.8
	Suckler cows production activity	64.0
	Heifers raising activity	36.7
	Calves male fattening activity	22.0
	Calves female fattening activity	22.0
	Calves male raising activity	22.0
	Calves female raising activity	22.0

Water requirements for beef (see Table 7) are affected by many factors, in particular dry matter intake, environmental temperature, and stage and type of production. While it is impossible to list specific requirements for beef with accuracy NRC (2000) points to the water equation developed by Hicks et al. (1988):

$$FWI = -18.67 + 0.3937 \times Tmax + 2.432 \times DMI - 3.870 \times PP - 4.437 \times DS$$

where FWI is free water intake (kg/day), $Tmax$ is the maximum temperature (°F), DMI is dry matter intake (kg/day), PP is precipitation (cm/day) and DS is the percentage of dietary salt.

The drinking water requirements of pigs are affected by the housing method, growth stage and feeding method used, and they are shown in Table 8.

Table 8 Drinking water requirements of pigs

Source	Category	Litres per day
Van der Leeden (1990)	Pigs (weight 30 lbs)	2.27
	Pigs (weight 60–80 lbs)	3.03
	Pigs (weight 75–125 lbs)	7.19
	Pigs (weight 200–380 lbs)	9.46
	Pregnant sows	15.52
	Lactating sows	20.44
Lardy et al. (2008)	Pigs (weight 25 lbs)	1.89
	Pigs (weight 60 lbs)	5.68
	Pigs (weight 100 lbs)	6.62
	Pigs (weight 200 lbs)	9.46
	Gestating sows	17.03
	Sow plus litter	22.71
Steinfeld et al. (2006)	Lactating sows	30.73
Ward and McKague (2007)	Pigs (weight 23–70 kg)	4.5
	Pigs (weight 70–110 kg)	9.0
	Gestating sows	15.0
	Lactating sows	20.0
Initial value in CAPRI	Sows for piglet production	20.0
	Pigs for fattening	9.0

Grazing sheep, particularly in the cooler seasons of the year, can require relatively little additional water beyond what they receive through forage.

Table 9 Drinking water requirements of sheep and goat

Source	Category	Litres per day
Van der Leeden (1990)	Sheep on range or dry pasture	4.16
	Sheep on good pasture	0.38
Lardy et al. (2008)	Ewes with lambs	11.36
	Rams	7.57
Steinfeld et al. (2006)	Sheep	13.90
	Goat	9.70
Ward and McKague (2007)	Feeder lamb	4.4
	Meat ewe	10.0
	Dairy ewe	10.4
Initial value in CAPRI	Sheep and goats for milk	10.4
	Sheep and goats for fattening	10.0

Hot, drier weather, however, will result in increased water intake. Like cattle, the drinking water requirements for sheep vary enormously according to diet, body weight and the number of lambs reared (see Table 9). Dietary factors influence water intake and water-to-feed ratios. Water requirements of poultry are related to feed consumption and to the air temperature, and are shown in Table 10.

Table 10 Drinking water requirements of poultry

Source	Category	Litres per day
Van der Leeden (1990)	Chickens (1–3 weeks of age)	4.54
	Chickens (3–6 weeks of age)	8.33
	Chickens (6–10 weeks of age)	13.25
	Chickens (9–13 weeks of age)	17.03
	Pullets	13.25
	Non-laying hens	18.93
	Laying hens (moderate temperatures)	23.66
Steinfeld et al. (2006)	Adult broilers (100 head)	37.60
	Laying hens (100 head)	29.83
Ward and McKague (2007)	Laying hens (1 000 head)	250.0
	Broilers breeders (1 000 head)	250.0
	Pullets	105.0
Initial value in CAPRI	Laying hens (1 000 head)	250.0
	Poultry for fattening (1 000 head)	250.0

2.3.3 Service water requirements

Apart from drinking water, livestock production also requires service water (cleaning production units, washing animals, cooling facilities, waste disposal).

Table 11 Service water requirements

CAPRI activity	Service water (l/head)
Dairy cows low yield	22.0
Dairy cows high yield	22.0
Light male cattle	11.0
Heavy male cattle	11.0
Light heifers for fattening	11.0
Heavy heifers for fattening	11.0
Suckler cows	22.0
Heifers for raising	11.0
Male calves for fattening	2.0
Female calves for fattening	2.0
Male calves for raising	2.0
Female calves for raising	2.0
Pigs for fattening	5.0
Sows	50.0
Sheep and goat breeding females	5.0
Sheep and goat for fattening	5.0
Laying hens	(l/1 000 head for poultry) 150.0
Poultry for fattening	(l/1 000 head for poultry) 90.0

Service water requirements depend on many factors, in particular the class of livestock and the production system. Estimates provided by Steinfeld et al. (2006) will be used as reference values (see Table 11).

2.3.4 Integration of livestock water use in the supply module of CAPRI

The sum of drinking and service water requirement gives total water requirement per day for each class of animal. Taking into account the length of the production period, this coefficient is translated to water requirement per head. That is, water requirements are modelled in a similar way to feed requirements. A new requirement constraint is entered in the supply model to indicate that water requirements by animals have to be covered. The term REQSW defines water requirements (both drinking and service water requirements) for each animal category, measured in m^3/head. The example of calculation of water requirements in case of Denmark is presented in Table 12.

Table 12 Calculation of water requirements for different types of animals for Denmark

CAPRI activity	**Drinking water (l/head/day)**	**Service water (l/head/day)**	**Process length (days)**	**Total water per animal (m3/head)**
Dairy cows low yield	80	22	365	37.2
Dairy cows high yield	110	22	365	48.2
Light male cattle	41	11	81	4.2
Heavy male cattle	48	11	207	12.2
Light heifers for fattening	30	11	91	3.7
Heavy heifers for fattening	35	11	234	10.7
Suckler cows	64	22	365	31.4
Heifers for raising	37	11	666	31.8
Male calves for fattening	22	2	349	8.4
Female calves for fattening	22	2	325	7.8
Male calves for raising	22	2	355	8.5
Female calves for raising	22	2	347	8.3
Pigs for fattening	9	5	126	1.8
Sows	20	50	365	25.6
Sheep and goat breeding females	10	5	365	5.6
Sheep and goat for fattening	10	5	111	1.7
Laying hens	250	150	365	146.0
Poultry for fattening	250	90	43	14.6

An additional equation is entered in the supply model to compute regional water use in the livestock sector, from the livestock-specific water use intensities and the herd size.

3. Scenario analysis with the water module

3.1 Key assumptions and inputs for the Baseline scenario

A general approach to jointly assess biophysical and socio-economic impacts of climate change consist of combining general circulation models (GCMs), global gridded crop models (GGCMs) and global agro-economic models (GAEMs). Biophysical models project crop yield effects of climate change under various climate scenarios (defined by GCMs), and those yield effects are incorporated into agro-economic models to evaluate impacts on production and prices. For this study, results from biophysical simulations were incorporated into the agro-economic model CAPRI, thus the integrated modelling approach allows for the analysis of the impacts of climate change on agriculture.

The CAPRI baseline is based on the mid-term projections for agricultural markets by DG-AGRI as well as long-term projections by other models. In view of the high degree of uncertainty surrounding long-term macroeconomic projections, the time horizon chosen for this study is 2030. The key inputs of the reference run for 2030 may be summarised as follows:

- Database with historical series up to 2013.
- Mid-term projections for agricultural markets based on DG-AGRI's outlook for 2020 (European Commission, 2013). Policy assumptions, as well as the macroeconomic environment, are in line with this outlook.
- Projections up to 2030, the relevant horizon for this study, reflect the agri-food market development and socioeconomic drivers as defined in shared socio-economic pathway (SSP) 2 or 'middle of the road'.[8]
- Biofuel trends up to 2030 come from the PRIMES energy model.[9]
- Trends on irrigation shares up to 2030 come from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (as in Delincé et al., 2015).
- Explicit coverage of the CAP (pillars 1 and 2), including the latest reforms in dairy and sugar sectors.

The baseline scenario for 2030 defines the reference situation and thus serves as a comparison point for the simulation scenarios defined in the previous section. The model provides simulated results both at the global level (around 40 trade blocks covering the globe) and at the regional level within Europe (around 280 NUTS 2 regions). New tables on irrigation have been added to the CAPRI graphical user interface (GUI) in order to show the disaggregation of crop activities into rainfed/irrigated variants (see Table 13).

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[8] The AgMIP project (von Lampe et al., 2014) provided a set of standardised scenario assumptions for agricultural model comparisons along the two axes of SSPs (O'Neill et al., 2014) and representative concentration pathways (RCPs; van Vuuren et al., 2014)

[9] http://www.e3mlab.ntua.gr/e3mlab/PRIMES%20Manual/The%20PRIMES%20MODEL%202013-2014.pdf

Table 13 Rainfed/irrigated areas and yields for EU-28

	Area (1000 ha)			**Yield (kg/ha)**		
	Aggregate	Rainfed	Irrigated	Aggregate	Rainfed	Irrigated
Soft wheat	21 067	20 425	643	6 846	6 837	7 139
Durum wheat	2 367	2 197	170	3 912	3 886	4 251
Barley	10 911	10 339	572	5 502	5 525	5 087
Grain maize	9 154	7 248	1 906	8 448	7 523	11 966
Paddy rice	470	0	470	9 849	0	9 849
Rape	5 913	5 849	64	3 672	3 670	3 930
Sunflower	5 279	4 994	284	2 272	2 217	3 231
Soya	771	770	1	2 383	2 382	2 903
Potatoes	1 443	1 085	359	34 900	31 059	46 521
Sugar beet	582	449	133	80 786	75 449	98 805
Tomatoes	251	121	129	64 045	57 255	70 421
Other vegetables	1868	1091	776	25 645	24 829	26 793
Apples, pears, peaches	666	485	181	22 660	18 852	32 848
Other fruits	2111	1407	704	5 149	4 467	6 510
Citrus fruits	546	172	374	20 835	22 636	20 010
Table grapes	88	51	37	19 485	15 886	24 388
Olives for oil	4761	3662	1099	2 550	2 055	4 201
Table olives	306	220	86	2 888	2 339	4 294
Wine	2536	2138	398	5 519	5 218	7 137

Source: Own elaboration from CAPRI-Water results.

3.2 Introduction of water pricing

An increase in the irrigation water price may reflect increased competition for water with other sectors, increased environmental awareness or improved monitoring of agricultural water use. Many studies show that proper water pricing acts as an incentive for the long-term sustainable use of water resources (Massarutto, 2003; Iglesias and Blanco, 2008; Kampas et al., 2012). The Water Framework Directive (European Commission, 2000), established a legal framework to achieve sustainable water management in the EU. This Directive requires Member States to establish river basin management plans and to ensure that water pricing policies provide adequate incentives for users to use water resources efficiently. Following 'the polluter pays' principle, the WFD requires Member States to develop water pricing policies that ensure that all users contribute in an appropriate way.

To date, water pricing in agriculture differs significantly throughout the European Union. In general, farmers pay only a small share of the total cost of irrigation water (OECD, 2010): approximately 2 eurocents per cubic metre in Europe (which equates to around 30 % of the total supply cost). Both the water supply cost and the share of cost recovery are highly variable across EU countries and regions, but little precise information on these costs exists. However, a hypothetical additional price of 5 eurocents per cubic metre of irrigation water can be assumed in all EU regions. This price increase corresponds to a cost recovery share of 100 % on average.

3.3 Climate-related yield shocks

The climate change scenarios implemented in this study have been designed to provide more detailed insights into the specific impacts in Europe when considering irrigation-related strategies. We started from a particular climate scenario under the AgMIP project (von Lampe et al., 2014), which provided a set of standardised scenario assumptions for agricultural model comparisons along the two axes of SSPs (O'Neill et al., 2014) and representative concentration pathways (RCPs; van Vuuren et al., 2014).

SSP 2, without climate change, underlies the CAPRI baseline through its inputs from the Global Biomass Optimisation Model (GLOBIOM) model. It implies middle-of-the-road assumptions for population, GDP growth and related variables. The climate change scenario investigated in this project implies strong climate change (radiative forcing levels of 8.5 W/m^2) according to the global circulation model HadGEM2-ES, translated into yield effects by the crop model DSSAT. The exogenous yield effects were translated into standardised model input via IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) and have been used in an earlier CAPRI analysis (Delincé et al., 2015), while maintaining the socioeconomic assumptions on GDP and population growth from SSP 2, as in the baseline.

This climate shock scenario has been previously been run using CAPRI, but with the standard version only. For this purpose, the IMPACT yields for irrigated and rainfed systems were aggregated to an average (Delincé et al., 2015). Here, we use differential yield effects for irrigated and rainfed crops in EU regions. As non-EU regions so far do not have irrigation defined explicitly, the climate shock will be implemented for them in the average form only.

3.4 Water availability

Whereas water scarcity already constrains economic activity in many regions, the expected growth of global population over the coming decades, together with rising prosperity, will increase water demand and thus aggravate these problems. Climate change poses an additional threat to water security because changes in precipitation and other climatic variables may lead to significant changes in water supply in many regions (Schewe et al., 2014). The impacts of climate change on water resources are, however, highly uncertain (IPCC, 2014).

Global climate models project decreases in renewable water resources in some regions and increases in others, albeit with large uncertainty in many places. Broadly, water resources are projected to decrease in many mid-latitude and dry subtropical regions, and to increase at high latitudes and in many humid mid-latitude regions. Even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation) and seasonal reductions of water supply due to reduced snow and ice storage. Availability of clean water can also be reduced by negative impacts of climate change on water quality (IPPC, 2014).

Focusing on Europe, annual river flow is projected to decrease in southern and south-eastern Europe and to increase in northern Europe, but quantitative changes remain uncertain (OECD, 2013). Strong changes in seasonality are projected, with lower flows in summer and higher flows in winter. As a consequence, droughts and water stress will increase, particularly in the south and in summer. Moreover, increased evaporation rates are expected to reduce water supplies in many regions. Increased water shortages are expected to increase competition for water between sectors (tourism, agriculture, energy, etc.), particularly in southern Europe where the agricultural demand for water is already high (OECD, 2013).

As projections on irrigation water availability are not easily available, defining a future scenario becomes particularly challenging. A consistent climate scenario would have to consider the effects of increasing water demand from other sectors as part of the macroeconomic framework, but this aspect of climate change had been neglected in the early AGMIP scenarios. It is difficult, therefore, to specify the appropriate change in water availability that should be investigated in this project. As a result, we selected an illustrative specification for this scenario, taking into account estimates from the literature (Gerten et al., 2011).

3.5 Irrigation efficiency

It might be expected that increasing water scarcity would trigger an endogenous increase in water use efficiency. This cannot be modelled in CAPRI in an explicit way, but scenario assumptions can be chosen accordingly. Therefore, only a hypothetical change in water use efficiency has been implemented. We assume an annual irrigation efficiency improvement of 0.1 % both for water application efficiency and for water transport efficiency. This efficiency increase can be viewed as an optimistic estimate and it is based on OECD (2013), which foresees small improvements in irrigation efficiency in Europe in contrast to other world regions.

3.6 Scenario narratives

In line with previous considerations, a baseline and two groups of different scenarios (water pricing (WP) and climate change (CC)) have been analysed:

- Baseline scenario BAS: assumes no explicit effects of climate change on crop yields between 2010 and 2030. At most, it indirectly includes climate change via some trend projections.
- Water pricing scenarios:
    - W1 (water price): additional price of 5 eurocents per cubic metre of irrigation water in all EU regions. This price increase corresponds to a cost recovery share of 100 % on average.
    - W2 (water price plus irrigation efficiency improvement): water price as in the previous scenario plus annual irrigation efficiency improvement of 0.1 % for both water application efficiency and water transport efficiency. As the increase in irrigation efficiency affects all crops and regions similarly, the only differential effect of this scenario – compared with the water price scenario – will be on the cost of irrigation water applied in the field, which will be lower.
- Climate change scenarios:
    - CC: equivalent to AGMIP S6 scenario, implying RCP 8p5 as given from the climate model HadGEM2-ES (Jones et al., 2011) and translated into yield effects by the crop model DSSAT (Hoogenboom et al., 2004), without a change in water availability from the baseline, and without change in irrigation efficiency.
    - CCLessW: AGMIP S6 scenario with within the EU – 30 % decrease in irrigation water availability from the baseline, no change in irrigation efficiency.
    - CCIrrEff: AGMIP S6 scenario with adaptation within the EU, 30 % decrease in irrigation water availability from the baseline, annual irrigation efficiency improvement of 0.1 % in both water application efficiency and water transport efficiency.

4. Scenario results

In this section – for the simulation horizon 2030 – the two water pricing and three climate scenarios are compared with the baseline scenario.

An additional price for irrigation water might have negative impacts on irrigation shares. The decrease in irrigated areas could be counterbalanced by an increase in rainfed areas as initial decline of production will increase prices and thus stimulate additional production from the use of inputs other that water, for example using rainfed land.

Yield effects due to climate change are identical across climate scenarios. To understand the impacts of these yield effects, it is important to keep in mind:

- Although yield effects are mostly negative, their magnitude differs greatly depending crop, management practice and region.
- Endogenous responses within each region (from yield elasticity and from production intensity) will lead to endogenous adjustments of yield changes.
- At the aggregate level, yields also change when weights for regions change in simulations.

The uneven biophysical effects of climate change on rainfed and irrigated crops deserve further clarification. Overall, rainfed crops are more negatively affected than irrigated crops under all climate scenarios (Rosenzweig et al., 2013; Müller and Robertson, 2014). Irrigation expansion is, therefore, one of the endogenous adaptation strategies to climate change.

In brief, at the EU regional level, producers adapt to climate change by altering production intensity, reallocating land across crop activities and shifting between rainfed and irrigated production. Other farm-level adaptation responses, such as changes in crop varieties, are not explicitly considered in this study. Beyond farm-level adaptations, CAPRI also simulates some market-level adjustments, such as changing regional patterns of production, consumption and trade.

4.1 Water pricing

Overall, an additional price for irrigation water will have significant negative impacts on irrigation shares. The decrease in irrigated areas for cereals and oilseeds will be compensated by an increase in rainfed areas for these crops. This follows as price reactions tend to stabilise the overall production level: an initial decline in irrigated areas will increase prices and thus stimulate additional production from the use of inputs other that water, for example using rainfed land. As illustrated in Table 14 the effects of scenarios W1 and W2 on land use and agricultural production are similar at the aggregate level. The net effect at the EU level will be a moderate increase in the area allocated to cereals and oilseeds (+0.3 % and +0.6 %, respectively) at the expense of the area allocated to set-aside (−1.2 %), while total agricultural area will increase only marginally (+0.1 %).

Nevertheless, effects on production differ across crops, as they are driven by two opposite forces: (1) the decrease in the relative profitability of irrigated crops compared with rainfed crops and (2) the translation of higher crop production costs into higher producer prices, which stimulate production.

Table 14 Effects of EU water pricing on activity levels and production (EU-28, percentage change from baseline)

	Scenario W1		**Scenario W2**	
	Activity level	Production	Activity level	Production
Utilised agricultural area	0.1	0.3	0.1	0.3
Cereals	0.3	0.1	0.3	0.1
Oilseeds	0.6	0.5	0.6	0.5
Other arable crops	–0.1	–0.1	–0.1	–0.1
Vegetables and permanent crops	0.0	0.3	0.0	0.3
Fodder activities	0.0	0.4	0.0	0.4
Set aside and fallow land	–1.2	0.0	–1.2	0.0
All cattle activities	–0.1	0.2	–0.1	0.2
Beef meat activities	–0.1	0.2	–0.1	0.2
Other animals	–0.1	0.1	–0.1	0.1

Source: Own elaboration from CAPRI-Water results.

For crops with high irrigation shares – which are also water-intensive crops – the cost effect dominates and drives down production in spite of increasing producer prices (Table 15). In contrast, crops with low irrigation shares and which are less water demanding – such as wheat and barley – benefit from the price increase triggered by the substitution effects and experience only a moderate cost increase such that their production increases. No significant difference is found between the two scenarios analysed.

Table 15 Effects of EU water pricing on crop producer price and crop production (EU-28, percentage change from baseline)

	Baseline (BAS)	**Scenario W1**		**Scenario W2**	
	Irrigation share	Production	Price	Production	Price
Soft wheat	3.1	0.3	0.4	0.3	0.4
Durum wheat	7.2	0.0	0.2	0.0	0.2
Barley	5.2	0.5	0.5	0.4	0.5
Grain maize	20.8	–2.7	1.1	–2.6	1.1
Paddy rice	100.0	–0.9	0.7	–0.9	0.7
Rape seed	1.1	0.0	0.2	0.0	0.2
Sunflower seed	5.4	–0.8	2.1	–0.8	2.1
Soya seed	0.1	–0.5	0.2	–0.5	0.2
Potatoes	24.8	–0.4	0.4	–0.4	0.4
Sugar beet	22.8	–2.4	1.1	–2.3	1.1
Tomatoes	51.6	–0.8	0.8	–0.7	0.8
Other vegetables	41.6	–0.3	0.9	–0.3	0.9
Apples, pears and peaches	27.2	–0.1	0.2	–0.1	0.2
Table grapes	33.4	–0.1	0.1	–0.1	0.1
Citrus fruits	68.6	–0.2	0.1	–0.2	0.1
Other fruits	42.4	–0.5	0.4	–0.4	0.4
Olive for oil	23.1	–0.9	2.2	–0.9	2.1
Table olives	28.1	–0.8	1.1	–0.8	1.1
Wine	15.7	–0.2	0.3	–0.2	0.3

Source: Own elaboration from CAPRI-Water results.

The effects on total and irrigated area are differential across crops. Crops highly dependent on irrigation will experience minor area increases (i.e. maize) or even area decreases (i.e. rice). In addition, the irrigated share of these crops will decrease only moderately (Table 16). In contrast, a strong decrease in the irrigated share is expected for less water-intensive crops (i.e. wheat). In scenario W1, the additional water price will reduce total EU irrigated area and irrigation water use by 24 %. In scenario W2, effects on total land are similar. However, as irrigation efficiency improves, the decrease in irrigated area will be smaller (23 %) and will be accompanied by a larger reduction on water use (almost 27 %).

Table 16 Effects of water pricing on irrigated area and water use (EU-28, percentage change from baseline)

	Scenario W1			**Scenario W2**		
	Total land	Irrigated land	Irrigation water use	Total land	Irrigated land	Irrigation water use
Utilised agricultural area	0.1	–23.8	–24.1	0.1	–23.2	–26.9
Soft wheat	0.4	–46.1	–71.0	0.4	–45.4	–71.9
Durum wheat	0.9	–73.1	–82.5	0.9	–72.1	–82.7
Barley	0.7	–68.7	–81.7	0.7	–67.4	–81.9
Grain maize	0.4	–34.1	–33.7	0.4	–32.8	–35.5
Paddy rice	–0.9	–0.9	–1.3	–0.8	–0.8	–5.4
Rape	0.0	–50.5	–74.6	0.0	–49.9	–75.2
Sunflower	1.4	–79.4	–84.1	1.4	–78.9	–84.6
Soya	–0.4	–58.2	–70.9	–0.4	–56.4	–70.1
Potatoes	0.3	–10.1	–15.2	0.3	–9.7	–18.2
Sugar beet	–0.2	–28.8	–31.3	–0.2	–27.6	–33.1
Tomatoes	–0.1	–4.1	–4.9	–0.1	–3.9	–8.8
Other vegetables	0.0	–3.3	–4.5	0.0	–3.1	–8.4
Apples, pears, peaches	0.0	–1.8	–2.5	0.0	–1.7	–6.6
Other fruits	0.1	–6.7	–12.0	0.1	–6.4	–15.4
Citrus fruits	–0.1	–1.8	–3.0	–0.1	–1.7	–7.0
Table grapes	0.0	–0.4	–0.5	0.0	–0.4	–4.8
Olives for oil	0.2	–8.5	–9.8	0.2	–8.2	–13.3
Table olives	0.0	–7.7	–8.1	0.0	–7.4	–11.8
Wine	0.0	–2.8	–5.2	0.0	–2.7	–9.1

Source: Own elaboration from CAPRI-Water results.

The effects of water pricing on crop yields is presented in Table 17. Regional disparities are noticeable. Water pricing will induce uneven effects throughout the EU. Country-level differential effects on irrigated land and water use are shown in Table 18.

Table 17 Effects of water pricing on crop yields (EU-28, percentage change from baseline)

	Scenario W1			**Scenario W2**		
	Aggregate yield	Rainfed	Irrigated	Aggregate yield	Rainfed	Irrigated
Soft wheat	–0.1	–0.3	15.8	–0.1	–0.3	15.7
Durum wheat	–0.9	–0.8	20.1	–0.9	–0.8	19.9
Barley	–0.2	–0.8	18.7	–0.2	–0.8	18.2
Grain Maize	–3.1	0.4	2.0	–3.0	0.3	2.0
Paddy rice	0.0	0.0	0.1	0.0	0.0	0.1
Rape	0.0	0.0	5.7	0.0	0.0	5.7

Sunflower	−2.2	−0.5	13.1	−2.2	−0.5	13.1
Soya	0.0	0.0	16.9	0.0	0.0	16.1
Potatoes	−0.7	−0.7	3.1	−0.7	−0.6	2.9
Sugar beet	−2.2	−1.4	4.1	−2.1	−1.3	3.9
Tomatoes	−0.7	−1.5	0.7	−0.7	−1.4	0.7
Other vegetables	−0.3	−1.0	0.9	−0.3	−1.0	0.9
Apples, pears and peaches	−0.2	−0.2	0.7	−0.1	−0.2	0.7
Other fruits	−0.5	−1.7	3.5	−0.5	−1.7	3.3
Citrus fruits	−0.1	−3.1	1.3	−0.1	−3.0	1.3
Table grapes	−0.1	−0.1	0.1	−0.1	−0.1	0.1
Olives for oil	−1.1	−0.4	2.3	−1.1	−0.4	2.2
Table olives	−0.8	−1.2	3.6	−0.8	−1.2	3.4
Wine	−0.2	−0.1	0.2	−0.2	−0.1	0.2

Source: Own elaboration from CAPRI-Water results.

Table 18 Percentage change from baseline in irrigated land and water use by EU Member State

	Baseline (BAS)	**Scenario W1**		**Scenario W2**	
	Irrigation share (%)	Irrigated land	Water use	Irrigated land	Water use
European Union	4.57	−23.8	−24.1	−23.2	−26.9
Sweden	1.06	−8.6	−9.7	−8.3	−13.2
Finland	0.39	−22.2	−23.2	−21.4	−25.7
Estonia	0.05	−10.1	−10.9	−9.6	−14.1
Latvia	0.04	−18.3	−44.7	−17.5	−45.2
Lithuania	0.04	−12.0	−16.3	−11.3	−19.2
Ireland	0.01	−17.8	−18.3	−16.9	−21.0
United Kingdom	0.37	−13.6	−13.8	−13.0	−16.9
Denmark	5.95	−26.1	−27.1	−25.0	−29.1
Netherlands	3.04	−9.4	−10.2	−9.0	−13.6
Belgium	0.17	−13.6	−16.8	−13.0	−19.7
Germany	1.42	−7.6	−14.6	−7.3	−17.7
Poland	0.22	−8.9	−18.4	−8.5	−21.3
Czech Republic	0.38	−13.5	−14.0	−12.9	−17.1
Slovak Republic	0.57	−46.1	−45.1	−44.6	−46.0
France	4.39	−30.5	−30.5	−29.2	−32.2
Austria	0.62	−12.3	−12.9	−11.8	−16.1
Hungary	2.30	−54.1	−54.0	−52.5	−54.8
Slovenia	0.20	−4.1	−4.6	−3.9	−8.5
Croatia	0.74	−11.2	−15.5	−10.7	−18.5
Romania	1.03	−62.2	−58.7	−60.8	−59.5
Italy	15.07	−15.1	−13.3	−14.5	−16.5
Bulgaria	1.58	−20.5	−56.6	−20.1	−57.6
Portugal	8.21	−22.7	−21.7	−22.3	−24.7
Spain	10.81	−29.0	−30.8	−28.7	−33.4
Greece	22.05	−16.3	−13.9	−15.9	−17.3
Cyprus	19.98	−14.0	−20.1	−13.6	−23.0
Malta	17.59	−0.8	−0.9	−0.8	−5.2

Source: Own elaboration from CAPRI-Water results.

Regional effects are shown in Figure 2 (irrigated land) and Figure 3 (water use).

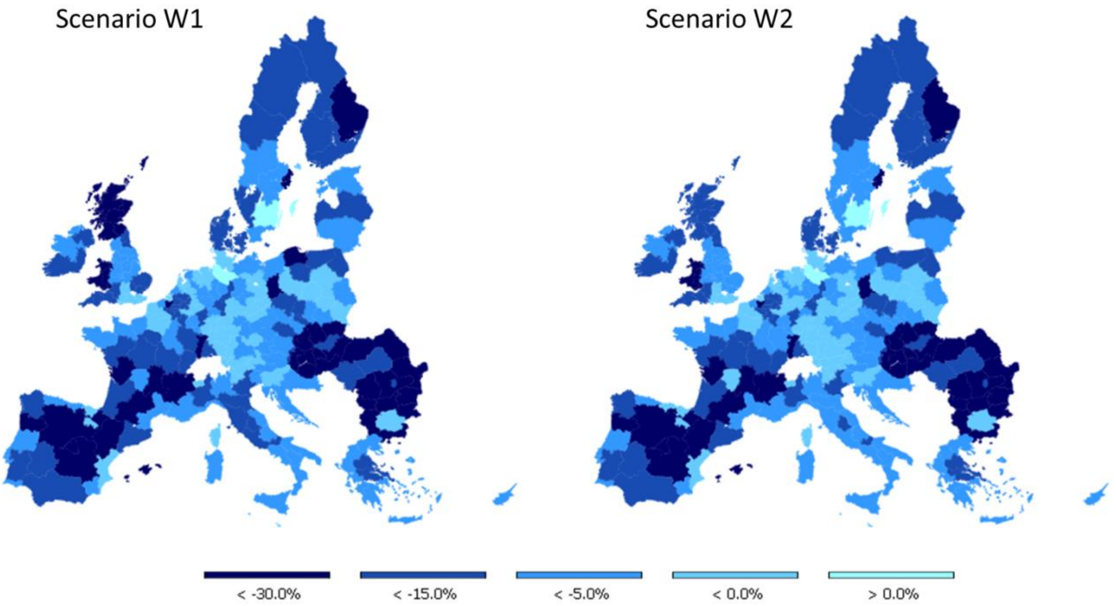

Figure 2 Percentage change from baseline in total irrigated land.

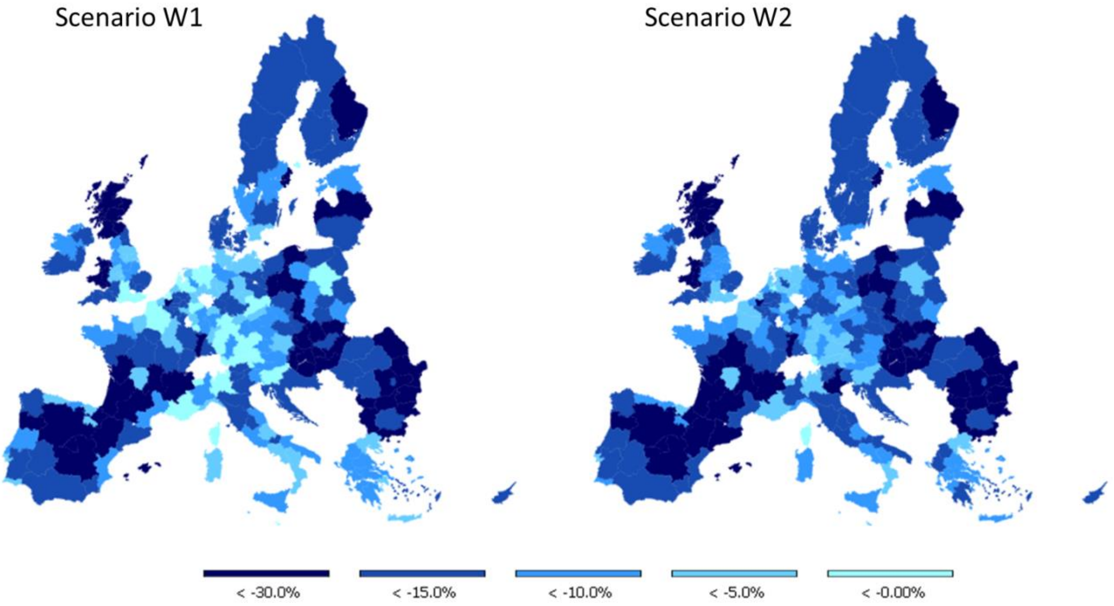

Figure 3 Percentage change from baseline in irrigation water use.

Looking at income effects, we find more positive effects in northern regions and negative effects in regions highly dependent on irrigation (Table 19).

Table 19 Effects of EU water pricing on agricultural income (percentage change from baseline)

	Scenario W1	**Scenario W2**
European Union	–0.3	–0.3
Sweden	0.2	0.2
Finland	0.5	0.5
Estonia	0.4	0.4
Latvia	0.8	0.8
Lithuania	0.7	0.6
Ireland	0.5	0.5
United Kingdom	0.3	0.3
Denmark	0.2	0.2
Netherlands	0.4	0.4
Belgium	0.6	0.6
Germany	0.7	0.7
Poland	0.3	0.3
Czech Republic	0.5	0.5
Slovak Republic	0.2	0.2
France	–0.1	–0.1
Austria	0.4	0.4
Hungary	–0.6	–0.6
Slovenia	0.6	0.6
Croatia	0.7	0.7
Romania	0.3	0.3
Italy	–0.9	–0.8
Bulgaria	0.4	0.4
Portugal	–3.6	–3.5
Spain	–0.9	–0.9
Greece	–4.4	–4.3
Cyprus	–5.9	–5.7
Malta	–5.9	–5.7

Source: Own elaboration from CAPRI-Water results.

4.2 Endogenous responses to climate change

In this section we analyse results from scenario CC (with crop yields influenced by climate change). Compared with the baseline, although yield effects strongly differ across products and regions, the overall effect is negative, driving up producer prices both globally and at EU level (Figure 4). This leads to mixed results on crop production, but to particularly severe effects in the case of grain maize. The findings of this study are in line with previous studies analysing a similar scenario (Witzke et al., 2014).

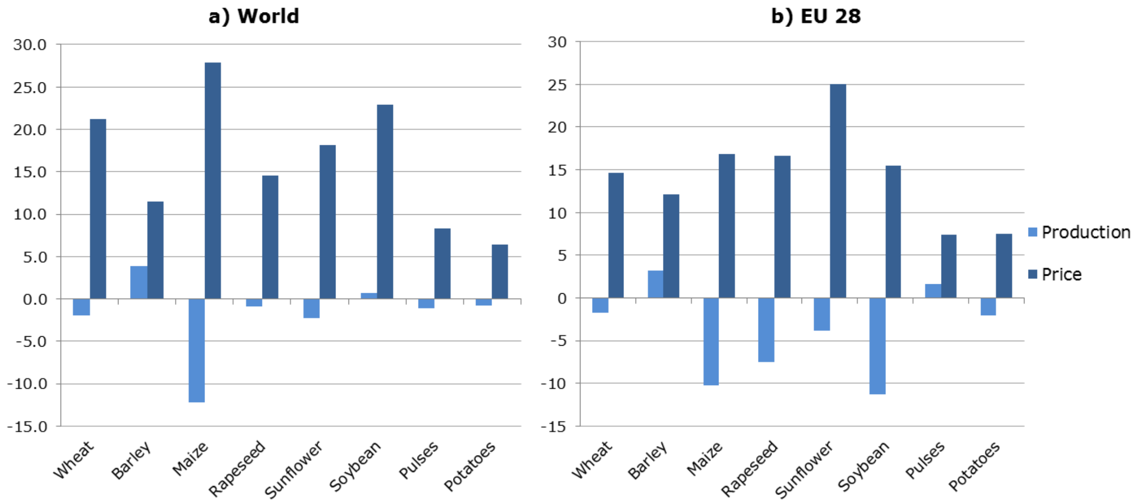

Figure 4 Effects of climate change on production and prices (percentage change from baseline).

To analyse the response of farmers to changing biophysical conditions and price levels, Figure 5 shows effects on endogenous yields and crop land allocation.

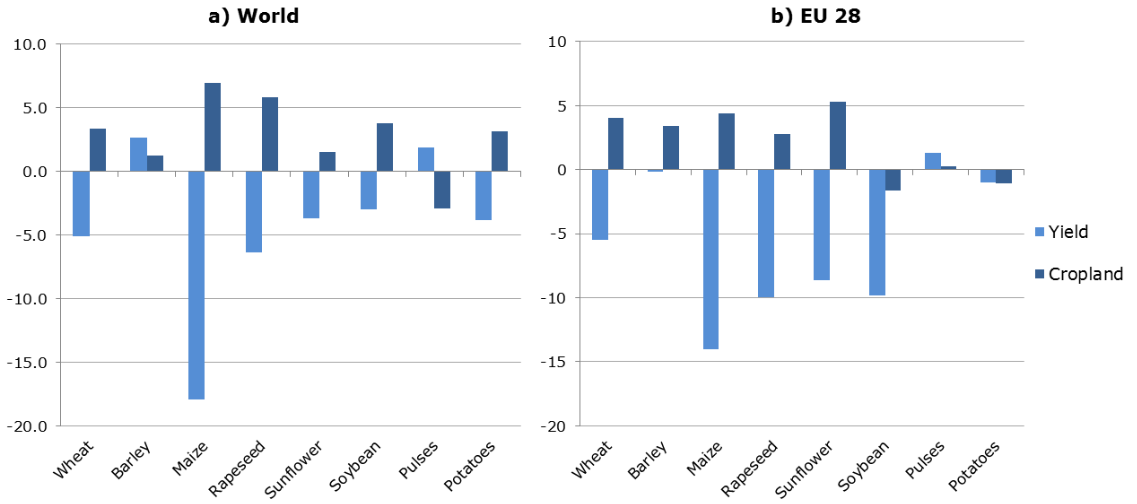

Figure 5 Effects of climate change on yields and land allocation (percentage change from baseline).

For non-EU regions, readers are reminded that this CAPRI version makes no distinction between irrigated and rainfed areas so the yield shocks and endogenous adjustments all occur in aggregate form only. Production effects in world regions and for the major crops are mainly driven by the distribution of yield shocks in these dimensions. For the EU impacts, Figure 6 highlights the large spatial variability of climate change impacts, confirming findings from other studies (Shrestha et al., 2013; Délincé et al., 2015; Blanco et al., 2015).

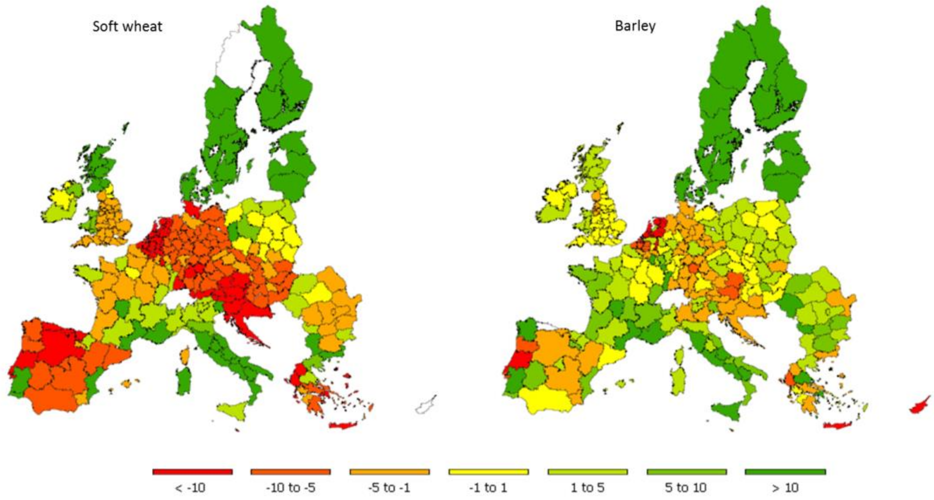

Figure 6 Regional production under scenario CC (percentage change from baseline).

Within the EU, differential effects for rainfed and irrigated crops can be analysed. Overall, yield effects are more negative for rainfed than for irrigated activities, as shown in Table 20 but their shares change endogenously. As a result, climate change induces significant substitution effects between irrigated and rainfed areas.

Table 20 Effects of climate change on EU yields (percentage change from baseline)

	Scenario CC		
	Aggregate yield	Rainfed	Irrigated
Soft wheat	–5.5	–5.9	5.2
Durum wheat	–8.3	–8.9	2.6
Barley	–0.1	–0.4	2.1
Grain maize	–14.3	–19.7	–4.2
Paddy rice	0.7	0.0	0.7
Rape	–10.0	–10.2	4.4
Sunflower	–8.6	–9.7	4.0
Soya	–9.8	–10.0	–3.4
Potatoes	–1.1	–13.9	6.7
Sugar beet	–11.2	–11.9	1.1
Tomatoes	–3.8	–15.3	2.6
Other vegetables	–2.4	–13.1	6.7
Apples, pears and peaches	–5.6	–11.1	–0.1
Other fruits	–6.1	–10.9	–1.5
Citrus fruits	–5.0	–7.4	–3.7
Table grapes	–4.3	–8.2	–2.1
Olives for oil	–4.7	–11.5	–0.3
Table olives	–4.3	–5.9	–3.0
Wine	–6.4	–7.9	–2.3

Source: Own elaboration from CAPRI-Water results.

As mentioned above, shifting from rainfed to irrigated crops is one of the endogenous adaptation strategies modelled. Figure 7 shows that irrigation rises particularly in those countries where the irrigation share was already high in the baseline situation. In most cases, rainfed yields are also more negatively affected by climate change in these countries. Therefore, irrigation plays a role as an adaptation strategy face to climate change.

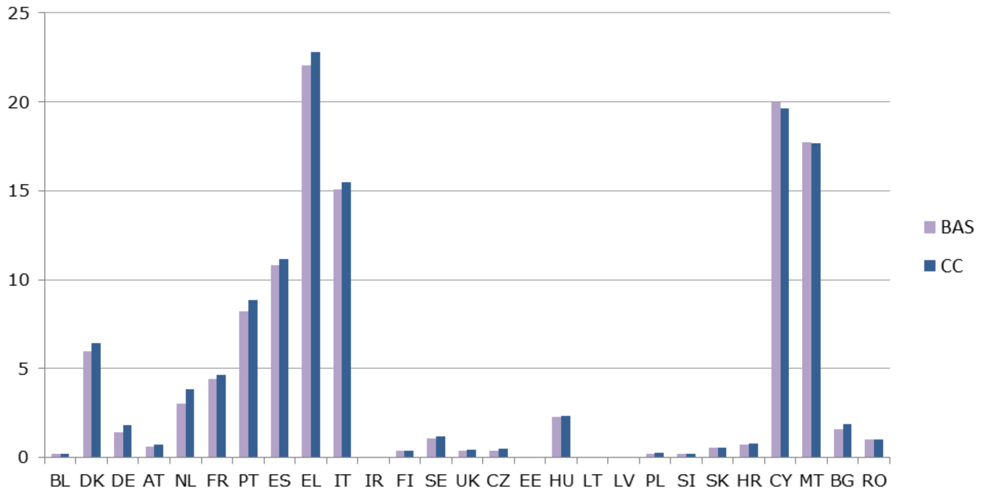

Figure 7 Irrigation share by Member State (percentage of utilised agricultural area) in Baseline (BAS) and CC scenario.

The adaptation contributions from irrigation are particularly visible in the case of the largest EU producer of grain maize, France. Expanding the maize irrigated area helps to limit the average yield and production decline (see Table 21). Hence, climate change will induce an increase in irrigated land and water use. However, irrigation water availability is limited, and thus a situation of water stress will arise in some regions/countries, driving up the opportunity cost of water. As a reaction to this scarcity signal, water will be reallocated to those activities with higher crop water productivity. This effect explains why the irrigated area of wheat decreases in France, in contrast to the increase in irrigated area of maize.

Table 21 Effects of climate change on soft wheat and maize in France (baseline levels and percentage change from baseline)

		Baseline (BAS)			**Scenario CC**		
		Area (000 ha)	Yield (kg/ha)	Supply (000 t)	Area	Yield	Supply
Soft wheat	Aggregate	42 87	80 75	34 612	3 %	−4 %	−1 %
	Rainfed	4 125	8 065	33 267	4 %	−5 %	−1 %
	Irrigated	162	8 318	1 345	−14 %	4 %	−11 %
Grain maize	Aggregate	1 840	10 974	20 189	3 %	−8 %	−5 %
	Rainfed	1 161	9 450	10 969	−5 %	−18 %	−22 %
	Irrigated	679	13 578	9 220	17 %	−2 %	15 %

Source: Own elaboration from CAPRI-Water results.

In scenario CC, climate change will induce an increase in irrigated land and water use, generating water scarcity situations in many regions. Table 22 summarises the climate effects on EU total and irrigated areas for major crops. Overall, irrigated area will increase for crops with high water productivity (e.g. maize, vegetables) while it will decrease for crops with lower water productivity (e.g. wheat). Water scarcity drives up the opportunity cost of water in agriculture and has similar effects to a price increase. As a result of increasing crop prices, agricultural income is expected to increase in most EU countries (see Figure 8). Overall, EU income increases by 9 %.

Table 22 Effects on EU irrigated area and water use (percentage change from baseline)

	Scenario CC		
	Total land	Irrigated land	Irrigation water use
Utilised agricultural area	1.1	6.0	5.2
Soft wheat	4.6	–2.7	–5.3
Durum wheat	–1.4	–27.0	–39.2
Barley	3.4	–13.9	–15.7
Grain maize	4.4	10.3	7.4
Paddy rice	0.7	0.7	0.8
Rape	2.7	–18.0	–16.2
Sunflower	5.3	5.1	3.7
Soya	–1.6	37.6	49.9
Potatoes	–1.1	35.3	28.5
Sugar beet	5.6	–29.0	–30.2
Tomatoes	–0.4	6.8	6.8
Other vegetables	0.1	19.0	16.8
Apples, pears and peaches	0.1	5.6	4.6
Other fruits	0.1	5.3	2.7
Citrus fruits	0.1	1.0	1.3
Table grapes	0.0	3.4	3.3
Olives for oil	0.0	11.8	12.4
Table olives	0.0	2.1	2.0
Wine	–0.1	4.7	3.0

Source: Own elaboration from CAPRI-Water results.

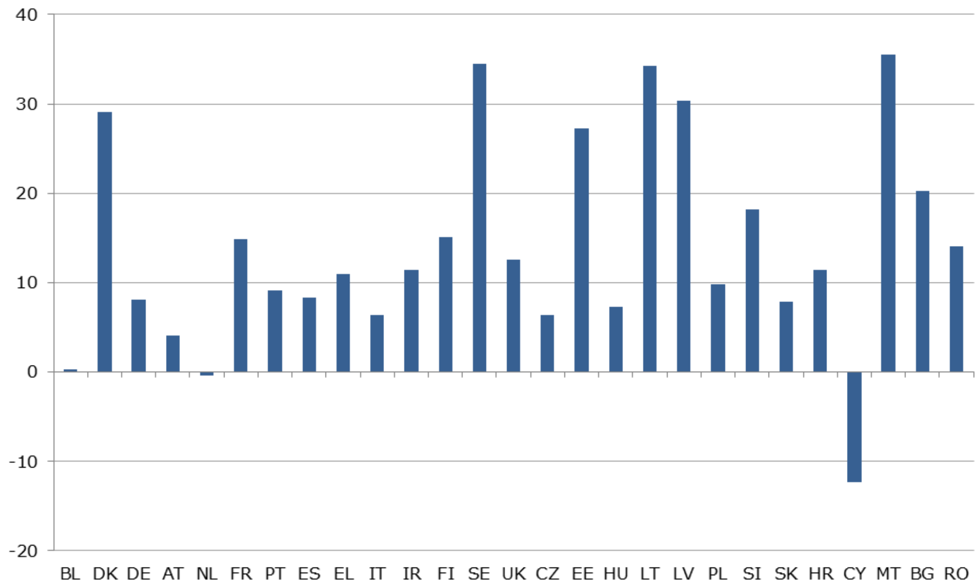

Figure 8 Effects of climate change CC on agricultural income (percentage change from baseline).

4.2 Increasing water scarcity and adaptation through irrigation efficiency

Scenario CC may be seen as optimistic in the sense that it does not account for the effects of climate change on water availability. Compared with scenario CC, the scenarios with reduced irrigation water availability in the EU with or without improving irrigation efficiency (CCLessW and CCIrrEff) will lead to increases in crop producer price within the EU (see Table 23). At the global level, as we assume no change in water availability outside the EU, and furthermore noting that the EU has only a small share in global production, the effects of all three scenarios analysed are not significantly different from each other.

Table 23 Effects of climate change on production and prices (percentage change from baseline)

	Scenario CCLessW				**Scenario CCIrrEff**			
	World average		EU average		World average		EU average	
	Production	Price	Production	Price	Production	Price	Production	Price
Wheat	−1.8	21.6	−1.4	15.4	−1.8	21.6	−1.4	15.3
Barley	4.2	12.2	3.7	13.2	4.2	12.1	3.7	13.0
Grain maize	−12.6	28.2	−15.5	18.9	−12.5	28.2	−14.9	18.7
Rapeseed	−0.9	14.7	−7.5	16.9	−0.9	14.7	−7.5	16.9
Sunflower	−2.3	19.1	−4.8	27.2	−2.3	19.0	−4.7	27.0
Soybean	0.7	23.0	−11.1	15.6	0.7	23.0	−11.1	15.6
Pulses	−1.1	8.4	0.7	8.3	−1.1	8.4	0.8	8.2
Potatoes	−1.1	7.0	−4.3	10.5	−1.0	6.9	−4.1	10.1

Source: Own elaboration from CAPRI-Water results.

Scenario CCLessW accentuates water stress (already significant in scenario CC in many regions). Even though water stress may have negative effects on productivity, it also may induce a more efficient use of water and the adoption of water-saving technologies. The scenario CCIrrEff represents this situation of improved irrigation efficiency. Overall, in these water-limiting scenarios, a shift from irrigated to rainfed crops is expected (Figure 9).

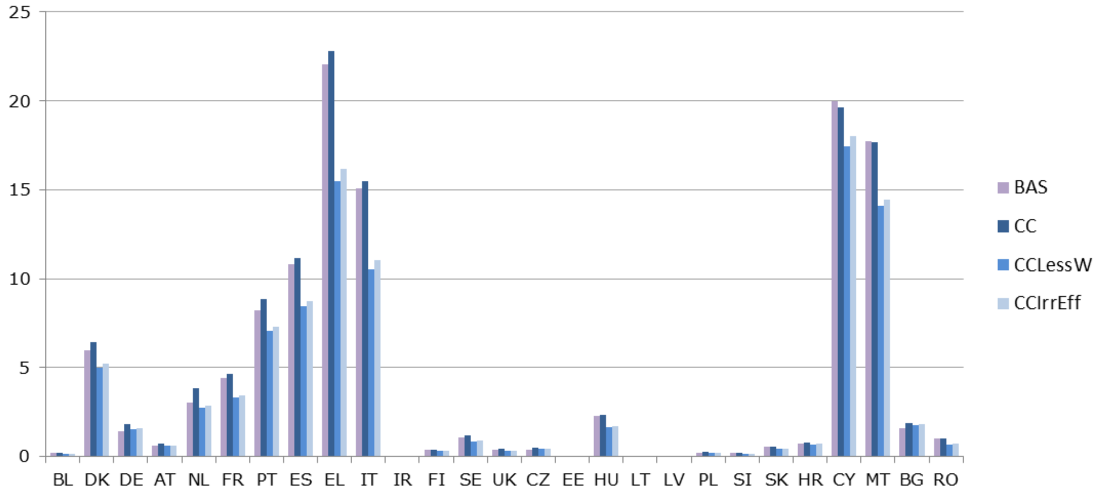

Figure 9 Irrigation share by Member State in Baseline (BAS) and climate scenarios (CC, CCLessW, CCIrrEff) (percentage of utilised agricultural area).

Overall, there will be a large decrease in irrigated area (23 %) and irrigation water use (25 %). When we assume an increase in irrigation efficiency (scenario CCIrrEff), the reduction in irrigation water use is similar to that observed in scenario CCLessW (25 %), but it can be attained with a much lower reduction in irrigated area by 19 % (see Table 24). Improving irrigation efficiency partially offsets the negative effects in production of the reduced water availability. As irrigation water becomes scarce, its allocation will move to water-productive crops.

Table 24 Effects on EU irrigated area and water use (percentage change from baseline)

	Scenario CC			**Scenario CCLessW**			**Scenario CCIrrEff**		
	Total land	Irrigated land	Water use	Total land	Irrigated land	Water use	Total land	Irrigated land	Water use
Utilised agricultural area	1.1	6.0	5.2	1.2	–22.8	–25.1	1.2	–19.7	–25.1
Soft wheat	4.6	–2.7	–5.3	5.1	–47.1	–67.9	5.0	–43.4	–65.2
Durum wheat	–1.4	–27.0	–39.2	–1.2	–85.3	–88.7	–1.1	–84.6	–89.0
Barley	3.4	–13.9	–15.7	3.9	–59.2	–67.4	3.9	–54.5	–64.2
Grain maize	4.4	10.3	7.4	3.5	–33.6	–33.4	3.7	–28.8	–31.8
Paddy rice	0.7	0.7	0.8	–3.4	–3.4	–4.6	–2.7	–2.7	–7.8
Rape	2.7	–18.0	–16.2	2.8	–58.8	–73.7	2.8	–56.2	–71.3
Sunflower	5.3	5.1	3.7	6.3	–54.4	–61.0	6.2	–48.7	–57.3
Soya	–1.6	37.6	49.9	–1.5	–35.5	–25.8	–1.5	–28.8	–23.0
Potatoes	–1.1	35.3	28.5	0.6	8.1	–4.4	0.3	11.7	–4.3
Sugar beet	5.6	–29.0	–30.2	6.0	–57.8	–58.3	5.9	–56.7	–59.3
Tomatoes	–0.4	6.8	6.8	–1.1	–10.4	–12.9	–0.9	–7.9	–14.0
Other vegetables	0.1	19.0	16.8	0.1	7.5	2.1	0.1	9.1	–0.5
Apples pears and peaches	0.1	5.6	4.6	0.0	0.2	–1.9	0.1	1.1	–5.1
Other fruits	0.1	5.3	2.7	0.2	–7.9	–21.1	0.2	–5.8	–21.1
Citrus fruits	0.1	1.0	1.3	–0.2	–0.7	–1.6	–0.1	–0.5	–5.4
Table grapes	0.0	3.4	3.3	0.0	2.0	1.6	0.0	2.2	–2.6
Olives for oil	0.0	11.8	12.4	0.8	–17.7	–19.3	0.7	–13.8	–18.8
Table olives	0.0	2.1	2.0	0.3	–33.7	–33.0	0.2	–28.7	–31.4
Wine	–0.1	4.7	3.0	–0.1	0.6	–5.4	–0.1	1.2	–8.3

Source: Own elaboration from CAPRI-Water results.

As a result of increasing crop prices, agricultural income is expected to increase under the three climate change scenarios (Table 25). As price effects are higher in scenario CCLessW (compared with scenario CC), income effects are stronger. EU income increases, on average, by 11 % compared with the baseline scenario, although there are high levels of heterogeneity across regions.

Table 25 Effects of climate change on agricultural income (percentage change from baseline)

	Scenario CC	Scenario CCLessW	Scenario CCIrrEff
European Union	9.7	11.0	10.8
Belgium	0.3	2.5	2.2
Denmark	29.1	31.3	31.1
Germany	8.1	10.2	9.9
Austria	4.1	5.4	5.2
Netherlands	–0.4	–0.4	–0.4
France	14.8	15.9	15.7
Portugal	9.1	9.5	9.6
Spain	8.3	10.6	10.3
Greece	11.0	10.3	10.4
Italy	6.3	6.7	6.7
Ireland	11.4	12.7	12.6
Finland	15.1	17.5	17.2
Sweden	34.5	36.9	36.5
United Kingdom	12.5	13.7	13.6
Czech Republic	6.3	7.3	7.1
Estonia	27.2	28.2	28.1
Hungary	7.3	8.1	8.0
Lithuania	34.3	35.9	35.7
Latvia	30.3	31.7	31.6
Poland	9.8	10.6	10.5
Slovenia	18.2	19.7	19.5
Slovak Republic	7.8	8.9	8.8
Croatia	11.4	13.5	13.2
Cyprus	–12.3	–12.4	–12.2
Malta	35.5	23.7	24.9
Bulgaria	20.2	21.4	21.2
Romania	14.1	15.3	15.2

Source: Own elaboration from CAPRI-Water results.

In the standard CC scenario, climate change will induce an increase in irrigated land and water use (Table 26). Irrigated area will increase for water-intensive crops (e.g. maize, fruits and vegetables), while it will decrease for less water-demanding crops (e.g. wheat). In the water-limiting scenario (CCLessW), a shift from irrigated to rainfed crops is observed. Overall, there will be a large decrease in irrigated area (23 %) and irrigation water use (25 %). When we assume an increase in irrigation efficiency (scenario CCIrrEff), the reduction in irrigation water use is similar to that observed in scenario CCLessW (25 %), but it can be attained with a much lower reduction in irrigated area (20 %).

Table 26 Effects of climate change on EU irrigated area and water use (percentage change from baseline)

	Scenario CC			**CCLessW**			**CCIrrEff**		
	Total land	Irrigated land	Irrigation water use	Total land	Irrigated land	Irrigation water use	Total land	Irrigated land	Irrigation water use
Utilised agricultural area	1.1	6.0	5.2	1.2	−22.8	−25.1	1.2	−19.7	−25.1
Soft wheat	4.6	−2.7	−5.3	5.1	−47.1	−67.9	5.0	−43.4	−65.2
Durum wheat	−1.4	−27.0	−39.2	−1.2	−85.3	−88.7	−1.1	−84.6	−89.0
Barley	3.4	−13.9	−15.7	3.9	−59.2	−67.4	3.9	−54.5	−64.2
Grain maize	4.4	10.3	7.4	3.5	−33.6	−33.4	3.7	−28.8	−31.8
Paddy rice	0.7	0.7	0.8	−3.4	−3.4	−4.6	−2.7	−2.7	−7.8
Rape	2.7	−18.0	−16.2	2.8	−58.8	−73.7	2.8	−56.2	−71.3
Sunflower	5.3	5.1	3.7	6.3	−54.4	−61.0	6.2	−48.7	−57.3
Soya	−1.6	37.6	49.9	−1.5	−35.5	−25.8	−1.5	−28.8	−23.0
Potatoes	−1.1	35.3	28.5	0.6	8.1	−4.4	0.3	11.7	−4.3
Sugar beet	5.6	−29.0	−30.2	6.0	−57.8	−58.3	5.9	−56.7	−59.3
Tomatoes	−0.4	6.8	6.8	−1.1	−10.4	−12.9	−0.9	−7.9	−14.0
Other vegetables	0.1	19.0	16.8	0.1	7.5	2.1	0.1	9.1	−0.5
Apples, pears Peaches	0.1	5.6	4.6	0.0	0.2	−1.9	0.1	1.1	−5.1
Other fruits	0.1	5.3	2.7	0.2	−7.9	−21.1	0.2	−5.8	−21.1
Citrus fruits	0.1	1.0	1.3	−0.2	−0.7	−1.6	−0.1	−0.5	−5.4
Table grapes	0.0	3.4	3.3	0.0	2.0	1.6	0.0	2.2	−2.6
Olives for oil	0.0	11.8	12.4	0.8	−17.7	−19.3	0.7	−13.8	−18.8
Table olives	0.0	2.1	2.0	0.3	−33.7	−33.0	0.2	−28.7	−31.4
Wine	−0.1	4.7	3.0	−0.1	0.6	−5.4	−0.1	1.2	−8.3

Source: Own elaboration from CAPRI-Water results.

5. Conclusions and outlook on potential improvements

5.1 Conclusions

Economic assessments of the impacts of climate change on agriculture that do not include farm- and market-level adjustments may overestimate the negative effects of climate change. In particular, an analysis of the interplay between irrigation water and food production is lacking in most previous studies. Nevertheless, water availability is already a limiting factor for agricultural production in many EU regions. The pressures on water are increasing and climate change may add additional risks and jeopardise the sustainable use of this vital resource. It is, therefore, necessary to include water stress on impact assessments.

In our study, we assess the effects of climate change on EU agriculture while accounting for several endogenous adaptations, including the shift between rainfed and irrigated crops. On the one hand, we find that irrigation plays a role as adaptation strategy, partially offsetting the negative effects on crop productivity. On the other hand, however, if irrigation expansion implies using more water, this increase in irrigation water use will place additional stress on water resources. Therefore, improved irrigation efficiency and, in general, improved water use efficiency, can reduce climate risks and make agriculture less vulnerable to changing climate conditions. Measures stimulating efficient water use are crucial to move towards a climate-resilient sustainable agriculture.

In terms of modelling efforts it may also be concluded that much is missed when neglecting irrigation, such that a natural next step in model development for the CAPRI system would be to extend the representation of irrigation to non-EU regions, a step that will also require to adjust to more serious data problems at the global level.

5.2 Limitations of the current approach

The current implementation still leaves ample room for future improvements.

The availability of data is critical for the quality of the final results. In the development phase, ad hoc assumptions or second choice data have been used to address data gaps. For example, while data on total irrigable and irrigated area per region are provided by EUROSTAT, crop-specific irrigated area is provided for only a selected group of crops. Moreover, regional data (NUTS 2 level) are provided only for 10 selected crops, and only for 2010. As a result, crop-specific irrigated areas are based on 2010 datasets. These assumptions may be amended or replaced as new data become available.

In addition, the scenario analysis has shown that improvements in the result 'exploitation' options have been very useful. This also helped in the assessment of scenario results in terms of their plausibility. Tables for an activity comparison (average, irrigated, rainfed) are provided, as well as tables for irrigation water use. However, additional tables may be useful, for example a general table on water balances or specific tables on the cost composition.

Whereas for some key activity groups the response parameters of CAPRI have been derived from an earlier econometric estimation (Jansson, 2007), the split of activities into irrigated and rainfed technologies had to rely on assumptions.

For long-run applications with drastically changing incentives, it would be a serious limitation if irrigation cannot start in regions where it has not previously been observed. Therefore, some tiny initial irrigated levels have been introduced into the model for irrigable crops, even if there was no irrigation in these regions in the base year. It is yet unclear whether this is a sufficient to achieve the desired responsiveness.

5.2 Further development of the water module

The water module could be further developed in three dimensions.

Improvement of the water database: a limiting factor for the development of the water module is the lack of homogeneous and accurate data at EU-wide level for a good number of relevant variables, such as irrigation costs, irrigation water use, irrigation efficiency, crop-specific irrigated areas, crop yields under rainfed and irrigated conditions, etc. Improvements in the water database are essential to enhance the performance of CAPRI-Water.

Water use balances at the EU level: one of the crucial improvements to CAPRI-Water will be to account for competition between agricultural and non-agricultural water uses in a more detailed way. This will require additional data series on water use by sector as well as water balances. Since CAPRI represents the agricultural sector at the regional level, water use balances should be defined at the regional level. Ideally, the possibility of taking into account interregional water flows should also be investigated. Water use by non-agricultural sectors could be computed as a function of water use intensity (e.g. domestic water use per capita) and the driving forces of water use (e.g. population). Future food–water scenarios may imply changes in both water use intensity and the driving forces of water use and, therefore, may imply changes both in irrigation water demand and irrigation water availability.

Irrigation and water use in non-EU regions: while the detailed supply models for EU regions present great advantages for integrating water considerations, the CAPRI market module faces similar limitations than other multi-commodity models to deal with crop–water relationships. The current CAPRI market model drives supply quantities by behavioural equations that do not distinguish between an area and a yield response. However, an approach to model land allocation in the global market model of CAPRI has been recently developed. A similar approach could be envisaged to integrate water allocation in the CAPRI market module.

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List of abbreviations

CAPRI	Common Agricultural Policy Regional Impact Analysis
EEA	European Environment Agency
EU	European Union
FADN	European Farm Accounting Data Network
FAO	Food and Agriculture Organization of the United Nations
FSS	Farm Structure Survey
GAEM	global agro-economic model
GCM	general circulation model
GGCM	global gridded crop model
GLOBIOM	Global Biomass Optimisation Model
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IPCC	Intergovernmental Panel on Climate Change
JRC-IPTS	Joint Research Centre – Institute for Prospective and Technological Studies
JRC-IES	Joint Research Centre – Institute for Environmental Studies
MS	Member State
NRC	National Research Council
NUTS	Nomenclature of Units for Territorial Statistics
OECD	Organisation for Economic Co-operation and Development
RCP	representative concentration pathway
SAPM	Survey on Agricultural Production Methods
SSP	shared socio-economic pathway
WFD	Water Framework Directive

Glossary

The water concepts and terminology used in this report follow as closely as possible the terminology used in official water statistics and, in particular, the EUROSTAT, FAOSTAT and Organisation for Economic Co-operation and Development (OECD) data sources. However, since some discrepancies exist across data sources, hereafter we clarify the terminology adopted in this report. This is also a useful part of the technical documentation when linked to Common Agricultural Policy Regional Impact Analysis (CAPRI) model variables, parameters or sets.

At the global level, the **water cycle** – also known as the hydrological cycle – describes the continuous circulation of water within the Earth's hydrosphere, mainly driven by solar radiation. Water moves through the cycle by the physical processes of precipitation, evaporation, transpiration, infiltration, runoff and subsurface flow. Human activities also greatly affect the individual components of the hydrological cycle, through actions such as water abstraction from ground and surface waters.

To analyse water resources at a national or regional level, a distinction must be made between internal and total renewable water resources.[10] **Internal renewable water resources** refer to the water resources resulting from precipitation within the borders of the region and are a combination of surface water and groundwater. **Total renewable water resources** are obtained by adding incoming surface water and groundwater flows to the internal renewable water resources.

The internal water resources figures are the only quantities that can be added together for regional or continental assessment. The computation of total renewable water resources requires the assessment of interregional water flows. By definition, total water resources are not summed up at the Member State (MS) or European Union (EU) level.

Water use balance refers to the influence of human activities on the water cycle. Here, a distinction is made between water withdrawal and water use. The following conventions for water user sectors are used in this report:

- Domestic: water used by households and other municipal water users.
- Industrial: water used in the manufacturing, mining and electricity generation sectors.
- Irrigation: water used by irrigation.
- Livestock: water used by livestock.

Water withdrawal is the gross amount of water extracted from any source, either permanently or temporarily, for use in any sector (irrigation, livestock, industrial or domestic). Water withdrawal is sometimes called water abstraction. This form of water can be either diverted towards distribution networks or used directly. It includes consumptive use, conveyance losses[11] and return flow.

Water use is the amount of water used in any sector. It is the part of the water withdrawn that reaches the final user. Water use is split into consumptive water use and non-consumptive water use.

Consumptive water use is the part of the water lost to the immediate water environment through evaporation, plant transpiration, incorporation in products or crops,

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[10] Here we use the term 'renewable' rather than 'fossil'; fossil water has a negligible rate of recharge on the human scale and can thus be considered 'non-renewable'.

[11] Losses include water that is lost to the supply, at the point of measurement, from a non-productive use, including evaporation from surface-water bodies and non-recoverable deep percolation.

or consumption by humans and livestock. Water consumption is sometimes called water depletion.

The difference between total water use and consumptive water use is the non-consumptive water use, or return flow. This is the part of the water that is not consumed and returns to either the surface water or the groundwater, thus becoming available for use again. For most water use sectors, only a small amount of water is actually consumed, whereas most of the water withdrawn is returned, probably with reduced quality, to the environment for subsequent use.

Water use efficiency is the ratio of consumptive water use to water withdrawal. Efficiency may be measured using different spatial scales, and figures may differ because of water reuse throughout the water cycle. In the case of irrigation, we will define water use efficiency as the ratio of the consumptive water to the water abstracted for irrigation. Water use efficiency may be broken down into water distribution efficiency (the ratio of total water delivered to the total water diverted for irrigation, sometimes differentiated into conveyance efficiency and distribution channels efficiency) and water application efficiency (the ratio of the effective irrigation water evapotranspirated to the field water applied, driven mainly by the irrigation method used).

Water stress measures the pressure put on water resources and aquatic ecosystems by the users of these resources. A conventional measure of water stress is the withdrawal-to-availability ratio. This is the ratio of total annual water withdrawals to total water availability.

Crop water requirement, irrigation requirement, irrigation water use and irrigation water abstraction are often used synonymously or without clear distinction. To avoid confusion, the terminology used in this study is presented hereafter.

Crop water requirement is the total amount of water required for transpiration by a well-managed crop grown under optimum growth conditions without water stress or nutrient stress. For practical purposes, the crop water requirement is calculated as the potential crop evapotranspiration avoiding the problem of clearly defining optimum growth conditions and optimum crop yield (FAO, 1996).

In agriculture, **potential yield** is defined as the maximum yield a variety can achieve under no input restriction conditions (potential yield is location specific because of climatic conditions). **Water-limited yield** is defined as the maximum yield under rainfed conditions (water-limited yield varies across regions because of climate and soil characteristics). **Actual yield** is defined as the yield actually achieved in a defined geographical region.

Crop net irrigation requirement is the amount of water that has to be applied in addition to rainfall to serve crop water requirements. It is expressed in millimetres per year or in m^3/ha per year (1 mm = 10 m^3/ha). Crop net irrigation requirement is commonly determined as the difference between crop water requirement (i.e. potential crop evapotranspiration) and the actual crop evapotranspiration under rainfed conditions or **effective precipitation**.[12]

Gross irrigation requirement is the quantity of water to be applied to the field, taking into account water losses at the field level. Some of the irrigation water may be lost by percolation rather than by crop evapotranspiration. Therefore, this water can potentially be reused for irrigation or recharge other water bodies.

Gross irrigation requirement represents only some of the total water abstracted for irrigation purposes. Additional water abstraction results from the need to compensate for losses during transport, including infiltration, percolation and evaporation.

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[12] In irrigation, effective precipitation is that portion of the total precipitation that is retained by the soil so that it is available for use in crop production.

Another common classification of water resources is the classification into blue and green water flows. **Blue water** is water in rivers, lakes and groundwater. **Green water** is water in the rooted zone of the soil originating directly from rainfall that is available to plants. According to this classification, crop evapotranspiration originating from effective precipitation is also referred to as green water or soil water. Irrigation water that is used to meet crop water requirements falls into the category blue water.

Crop water productivity is the ratio of net benefits from crop production to the amount of water used. Physical water productivity is the crop output per unit of water used (often expressed in kg/m^3), while economic water productivity is defined as the value derived per unit of water used. Water productivity can be expressed either per unit of water used or per unit of water consumed. Economic water productivity per unit of water use will be used in this study.

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