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Abstract: When assessing the radiological impacts of radioactive waste disposal, irrigation using water contaminated with releases from the disposal system is a principal means of crop and soil contamination.
In spite of their importance for radiological impact assessments, irrigation data are scarce and associated with considerable uncertainty. Further uncertainty arises from the influence of climate and soil type change.

In this work we provide irrigation data relevant to a range of climatic, soil and crop characteristics for use in radiological impact assessments derived using the crop growth model AquaCrop.
The data were validated using measured irrigation rates reported in the literature.
We also compared the AquaCrop estimates with those obtained from empirical methods which have been proposed for use in radiological impact assessments.
Further, we analysed the AquaCrop irrigation data using mixed effects modelling to establish the relationships between irrigation requirement, climate, soil and crop type.

Irrigation estimates from all models were within the range of measured values reported in the literature.
The estimates from the AquaCrop, however, may be more appropriate for conservative radiological assessments than those from the empirical methods.
The use of mixed effects modelling allowed for the characterisation of the variability in climate effect on irrigation between crops, and in contrast to the empirical methods discussed in this paper, the AquaCrop and the mixed-effects models illustrated the influence of soil characteristics on the irrigation requirement.
The approach is relevant for generic dose assessments and as a means of obtaining irrigation requirement for a specific site under different climate conditions.

To the best of our knowledge, this is one of the most comprehensive analyses of irrigation data in the context of radiological impact assessment currently available.

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Highlights

- Generic irrigation data for radiological assessments are scarce
- We derive irrigation data using multi-crop and empirical models
- All derived values were within reasonable range of measured data
- The values from the multi-crop are more suitable for conservative assessments

Derivation of irrigation requirements for radiological impact assessments

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Abstract

When assessing the radiological impacts of radioactive waste disposal, irrigation using water contaminated with releases from the disposal system is a principal means of crop and soil contamination. In spite of their importance for radiological impact assessments, irrigation data are scarce and associated with considerable uncertainty. Further uncertainty arises from the influence of climate and soil type change.

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Keywords: Crop irrigation requirement, AquaCrop, Linear mixed-effects modelling, Radiological impact assessment

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1. Introduction

When assessing the radiological impacts of radioactive waste disposal, one critical situation to consider is potential groundwater contamination resulting from releases of radionuclides from surface or underground repositories. Irrigation with groundwater contaminated with radioactive substances is a principal means of crop and soil contamination through direct interception by foliage, deposition and mixing within the root zone soil and subsequent uptake by plant roots. Therefore, the amount of contaminated irrigation water applied is likely to influence the activity concentrations in crops and soils and the estimated radiological exposure of humans. The significance of this irrigation pathway has been acknowledged by many researchers (e.g. Olyslaegers et al., 2005; Pröhl et al., 2005).

In spite of their importance for radiological impact assessments, reliable irrigation data are lacking for several reasons including limited obligation to measure water abstraction, weak enforcement of legal obligations and illegal abstraction. Moreover, differences in the methodologies applied to assess irrigation abstraction (water metering, questionnaires, water use coefficients and model-based estimates) result in large differences between reported values (Wriedt et al., 2009).

As a result, the irrigation data available for radiological assessments are associated with considerable uncertainty. For instance, the widely used assessment code RESRAD (Yu et al., 2001) assumes generic irrigation rates of 200 and 1000 mm y^{-1} for humid and arid regions, respectively, but recommends use of site-specific data when available. In their model developed to estimate crop contamination from irrigation with radioactively contaminated water, Bergström and Barkefors (2004) assumed an irrigation rate of 150 mm y^{-1} irrespective of crop type. Kłos and Albrecht (2005) used a value of 160 mm y^{-1} for cereals, potato, root, leafy and fruit vegetables growing under temperate conditions in Eastern France. In their assessments, Pröhl et al. (2005) used values between 2 and 126 mm y^{-1} for grass, 0 and 120 mm y^{-1} for maize, 0 and 160 mm y^{-1} for cereals, 11 and 436 mm y^{-1} for leafy vegetables and 0 and 414 mm y^{-1} for fruit vegetables. Olyslaegers et al. (2005) reported values ranging from 29 to 260 mm y^{-1} for a range of crops. Recently, Grolander (2013) proposed irrigation values for Sweden in the range between 15 and 125 mm y^{-1}.

Further uncertainty is contributed to irrigation data by climate and soil type change. Present-day climate and landscape characteristics are likely to change within the time frames of the impact assessment of long-lived radionuclides (up to 1 million years). Van Geet et al. (2012) described possible sequence of future climate states in Belgium based on long-term projections reported in the literature with the objective of evaluating how climate predictions can be treated in long-term safety assessments of radioactive waste disposal facilities. These authors report that for the next few thousands of years the climate in northern Belgium would be characterised by moderately warmer temperatures with a similar overall degree of water availability to the present but with drier summers (i.e subtropical conditions). This period of subtropical conditions would be followed by a period of boreal (cold with no permafrost) and tundra (cold with permafrost) conditions.

In this paper:

- We set up the AquaCrop model using weather data from meteorological stations in regions with climates similar to those reported by Van Geet et al. (2012) and data representative of typical soils and crops in Belgium (Section 2.2).
- We derive crop irrigation requirements using the model setup from Section 2.2 and we substantiate the approach and the estimated irrigation requirements in Section 3.2.1.
- We compare the AquaCrop approach to empirical methods previously proposed to estimate irrigation requirements for use in radiological impact assessments and we demonstrate the magnitude of differences that can occur between process-based and empirical approaches (Section 3.2.2).
- Finally, we derive and discuss the optimal linear regression model (LMM) to describe the simulated irrigation data (Section 3.2.3) and we draw conclusions from the model about the effects of climate, soil and crop on irrigation requirement (Sections 3.3 to 3.5).

2. Materials and methods

2.1. Simulation of crop irrigation requirement: AquaCrop model

AquaCrop is a crop water productivity model developed by the Land and Water Division of Food and Agricultural Organisation of the United Nations. The model is used for the development of (deficit) irrigation schemes, agriculture management strategies and scenario analysis. It strikes a balance between accuracy, simplicity, robustness, and ease of use (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009). The model calculates the cumulative dry aboveground biomass production during the growing season as follows:

$$B = WP^* \sum_{i}^{n} \frac{Tr_i}{ET_{0i}} \tag{1}$$

where B is the aboveground dry biomass produced during the growing season (g m^{-2}), WP^* is the crop water productivity (g m^{-2}), Tr_i is the daily crop transpiration (m day^{-1}) and ET_{0i} is the daily reference evapotranspiration (m day^{-1}).

The model uses daily time steps to represent the dynamic behaviour of the environmental variables that affect crop growth process, i.e. water supply, soil evaporation, crop transpiration and air temperature. It also accounts for the effect of water and temperature stress on fundamental aspects of the growth (e.g. canopy growth and stomatal conductance). The main components of the soil-plant-atmosphere continuum and the parameters driving the model are shown in Fig. 1.

AquaCrop has been successfully validated and applied extensively to a wide range of environmental conditions and crops (e.g. Stricevic et al., 2011; Araya et al., 2010; Geerts et al., 2009; Heng et al., 2009).

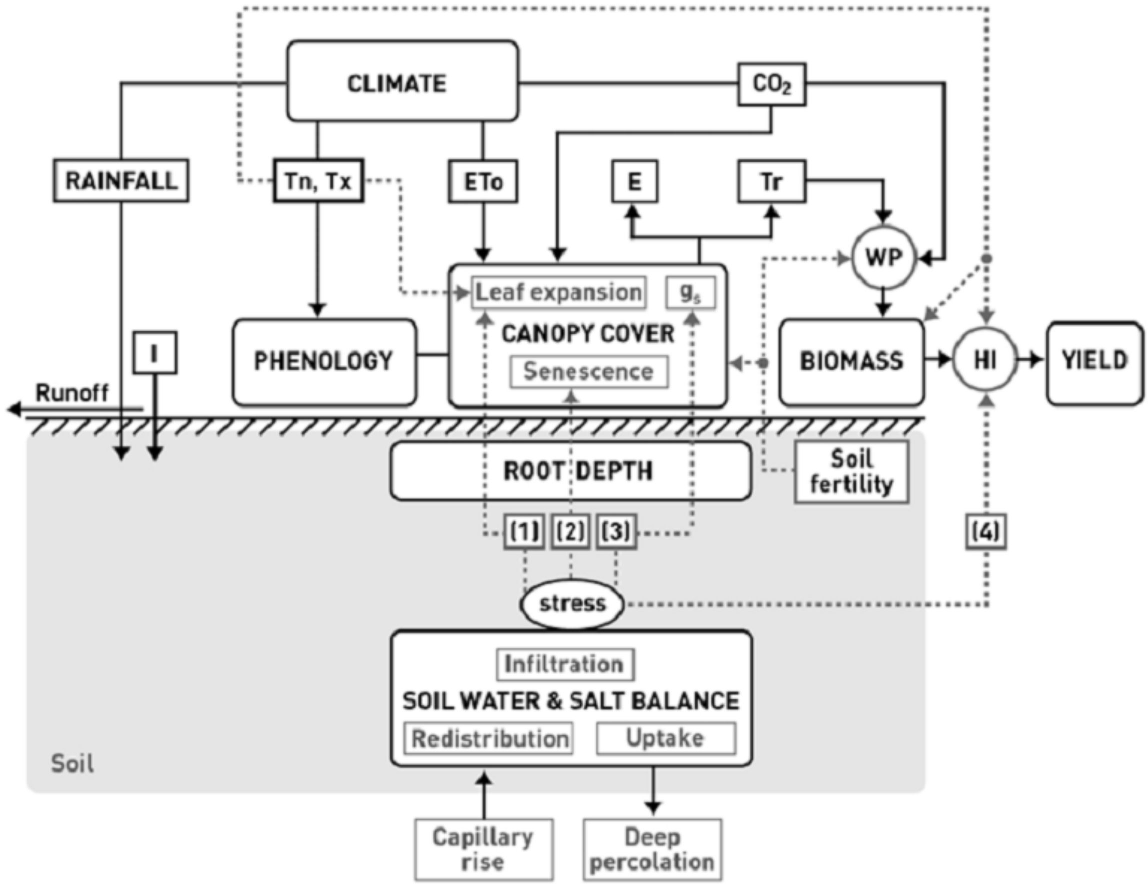

Figure 1: Chart of AquaCrop indicating the main components of the soil-plant-atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield (Steduto et al., 2009). I: Irrigation; Tn: Min air temperature; Tx: Max air temperature; ET_0: Reference evapotranspiration; E: Soil evaporation; Tr: Canopy transpiration; gs: Stomatal conductance; WP: Water productivity; HI: Harvest Index; CO_2: Atmospheric carbon dioxide concentration; (1), (2), (3) and (4): different water stress response functions. Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks.

2.2. AquaCrop setup

We setup AquaCrop using data representative of different climate, soil and crop combinations. The climates were selected on the basis of the projected future climates for north-eastern Belgium (Mol-Dessel region). The soils represent typical arable soils in the region and the crops were selected as representative of major components of the human diet as appropriate for dose calculation. Further description of AquaCrop parameterisation process is given below.

2.2.1. Climatic data

Climatic data representative of three different climates (i.e. climate analogues), based on the climate change projected for the study region described earlier, were used in the AquaCrop setup: temperate oceanic, temperate continental and Mediterranean. Although boreal conditions are projected to occur in Belgium in the long-term, irrigation is unlikely under these conditions due to unfavorable agricultural conditions. Temperate climate with a continental effect is common in large parts central and eastern Europe (e.g. eastern Germany) and is projected to occur over the Meuse/Haute-Marne region in northeastern France at around 175 000 years after present (Brulhet et al., 2004). Therefore, it has some relevance in the Belgian context.

Figure 2: Locations of the meteorological stations which provided time series of weather data for temperate oceanic (Dessel: 51°13′ N, 5°6′ E), temperate continental (Blindern: 59°56′ N, 10°43′ E) and Mediterranean (Malaga: 36°40′ N, 4°29′ W) climates.

For the present-day temperate condition daily maximum and minimum air temperatures, precipitation, and ET_0

between 1979 and 1998 were available from the local weather station operated by SCK•CEN (Belgium). In addition to the aforementioned variables (except ET_0), daily sunshine hours, relative humidity and wind speed for the Mediterranean and continental climates for the same period were obtained from the European Climate Assessment & Dataset provided by the weather stations at Blindern (Norway) and Malaga Aeropuerto (Spain). Geographical locations of these sites are shown in Fig. 2. The climatic data were used to calculate ET_0 for the Mediterranean and continental climates using the FAO ET_0 calculator based on the method of Allen et al. (1998).

2.2.2. Soil data

The root zone (A horizons) of typical agricultural soils in the Dessel region were simulated. The soils are light sand loam (P), loamy sand (S) and sand (Z) with moderately drained B horizon and obvious accumulation of organic matter and/or iron. The physical characteristics of the A horizons of these soils were obtained from the Belgian Aardewerk soil information database (Van Orshoven and Vandenbroucke, 1993) which provides detailed information for a large number of soil profiles across Belgium. Soil hydraulic characteristics were derived from soil texture and organic matter content using the pedotransfer functions (PTFs). There are many PTFs available for estimating soil hydraulic characteristics from soil physical properties including those developed by Vereecken et al. (1989) for Belgian soils. For this work, we used those of Saxton and Rawls (2006) because they are widely applied and were shown to perform better than those of Vereecken et al. (1989) when estimating soil field capacity and wilting point moistures (Givi et al., 2004). Estimated field capacity, wilting point moisture and saturated hydraulic conductivity are presented in Table 1.

Table 1: Physical and hydraulic characteristics for the A horizon and its subdivisions (Ap: the ploughing layer and A2: the layer of maximum leaching, or eluviation, of clay and iron) of the agricultural soils considered in this study. θ_{WP}, θ_{FC} and θ_{S} are the volumetric moisture at the wilting point, field capacity and saturation, respectivley, and K_S is the saturated hydraulic conductivity.

Soil class	**Horizon**		**Texture**			**Org. C**	**Hydraulic characteristics**			
	Type	Depth	Sand	Silt	Clay		θ_{WP}	θ_{FC}	θ_{S}	K_S
		cm	vol%	vol%	vol%	wt%	vol%	vol%	vol%	cm d^{-1}
P	Ap	26	53	39	8	0.6	5	17	40	86
	A2	26	53	39	8	0.2	5	17	39	79
	A2	16	56	37	7	0.1	4	15	38	94
S	Ap	11	78	17	5	1.7	4	11	44	214
	Ap	16	82	16	2	0.8	1	8	43	317
Z	Ap	22	96	2	2	1.3	2	5	48	386
	A2	12	97	1	2	0.2	0.4	4	43	482

2.2.3. Crop data

For our work, AquaCrop was parameterised for green beans, potato and wheat. These crops are key food crops in the Belgian diet and they are representative of the main crop categories often considered in radiological impact assessment models. Crop parameters in the AquaCrop simulation model are divided into a) conservative (generally applicable for a particular crop species across a wide range of environmental conditions) and b) non-conservative (specific for local cultivars and conditions such as length of the growing period, sowing date, maximum rooting depth).

The AquaCrop crop-specific parameter values under temperate maritime and continental conditions were obtained from Vanuytrecht (2013). The author first identified the model parameters with the highest impact on the predicted crop yield through a global sensitivity analysis (Vanuytrecht et al., 2014). Next, they calibrated those parameters for green beans, potato and winter wheat and validated the calibrated model using actual data collected from farmers fields in Belgium, the Netherlands and Northern France (these regions are geographically near and similar in climate). For the simulation of potato and wheat growth under Mediterranean conditions, we used the default crop parameter values available from AquaCrop database. The default values for potato have been calibrated based on field observations under mild desert conditions in South America and the default values for wheat have been calibrated based on field observations on spring wheat under Mediterranean conditions in Europe. Due to the lack of experimental data, green beans data obtained from field observations under the temperate climate were used to simulate growth under all climates.

Key crop parameters and their values used in our study are given in Table 2.

Table 2: Conservative AquaCrop parameters calibrated on field observations from temperate regions in Belgium. The default values available in the AquaCrop database (calibrated on field observations from warm regions) are given in parentheses. No default values are available for green beans in the AquaCrop database. t_{base} is the base temperature below which crop development does not progress, t_{upper} is the upper temperature above which crop development no longer increases with an increase in temperature, ccs is the soil surface covered by an individual seedling at 90% emergence, cgc is the increase in canopy cover, cdc is the decrease in canopy cover, WP^* is the water productivity normalised for ET_0 and CO_2 and $stbio$ is the minimum growing degrees required for full biomass production (a full list of the conservative and non-conservative AquaCrop parameters is given in the Appendix). GDD (growing degree days) is a measure of heat accumulation used to simulate crop development.

Crop	t_{base}	t_{upper}	ccs	cgc	cdc	WP^*	$stbio$
	°C	°C	cm^2	Fraction GDD^{-1}	Fraction GDD^{-1}	g m^{-2}	GDD d^{-1}
Beans	6 (-)	30 (-)	5 (-)	0.014 (-)	0.2 (-)	15 (-)	14 (-)
Potato	2 (7)	26 (35)	20 (10)	0.009 (0.016)	0.008 (0.002)	18.5 (18)	8 (7)
Wheat	2 (0)	26 (26)	0.75 (1.5)	0.008 (0.005)	0.008 (0.004)	18.5 (15)	8 (14)

Typical crop sowing and planting dates may vary with variety, location and climate (e.g. early vs. late maturing, late and short seasons in cold temperate and continental regions compared to long and early seasons in warm subtropical climate). Moreover, some crops may be cultivated all year round (e.g. potato). In this study, the cropping seasons with maximum irrigation requirements were selected. Therefore, planting dates were set to 25^{th} April for potato, 25^{th} May for beans and 28^{th} October for wheat.

2.2.4. Crop irrigation criteria

For irrigation, a sprinkler system with 100% soil surface wetting is assumed. Irrigation was applied when 30% of the root zone readily available water (depth of water that is the difference between field capacity and the threshold for stomatal closure) has been depleted. The root zone was irrigated back to field capacity. These timing and depth criteria guarantee no crop water stress and therefore represent maximum levels of irrigation.

2.3. Empirical methods for estimating crop irrigation requirements

There are a large number of empirical methods that can be used to calculate the reference evapotranspiration when detailed meteorological data are not available (e.g. Blaney-Criddle and Hargreaves-Samani methods). In our study, we focus on the methods of Thornthwaite and Becker due to their popularity in the radiological impact assessment community (Brulhet et al., 2004). We used these empirical methods to estimate irrigation requirements under the different climatic conditions and compared their estimates with those obtained using AquaCrop. The two approaches are briefly described below.

2.3.1. Thornthwaite method

Shaw (1998) expanded the method of Thornthwaite (1948) to estimate potential evapotranspiration, PE_m to serve the needs of irrigation engineers[1]. This method is based mainly on temperature with an adjustment being made for the number of daylight hours. An estimate of the potential evapotranspiration, PE_m, calculated on a monthly basis, is given by:

$$\mathrm{PE}_m = 16N_m\Big(\frac{10T_m}{I}\Big)^a \tag{2}$$

where m is the months 1, 2, 3...12, N_m is the monthly adjustment factor related to hours of daylight, T_m is the monthly mean temperature °C, I is the heat index for the year, given by:

$$I = \sum_m \Big(\frac{T_m}{5}\Big)^{1.5} \tag{3}$$

and:

$$a = 6.7\times10^{-7}I^3 - 7.7\times10^{-5}I^2 + 1.8\times10^{-2}I + 0.49 \tag{4}$$

[1]The BIOCLIM report relied upon the 1^{st} edition of Shaw's book while the authors of this paper consulted the 3^{rd} edition

The monthly adjustment is made for months in which $T_m > 0$ °C. PE_m is set to zero for months in which $T_m \leq 0$ °C. The N_m values (Table 3) were calculated following the procedure described in Shaw (1998) (Appendix 11.1.2) from the maximum mean daily possible sunshine hours.

For each month we subtracted PE_m from the precipitation to estimate moisture excess. Negative values of moisture excess correspond to a moisture deficit. Annual irrigation requirement IR was calculated as the sum of monthly moisture deficits:

$$\mathrm{IR} = \sum_m P_m - PE_m \tag{5}$$

2.3.2. Becker method

A direct approach to the estimation of irrigation requirements (Becker) was suggested within the BIOCLIM project (Brulhet et al., 2004) for use with impact assessments of radioactive waste disposal. The basis of the estimate is:

$$\mathrm{IR} = \sum_m P_m - K_m T_m \tag{6}$$

where K_m is a coefficient that depends both on T_m and the month:

$T_m < 5$°C: $K_m = 0$

$T \geq 5$°C: $K_m = 2$ (October to March), 3 (April and September), 4 (August), 5 (May and July), 6 (June). The summation in (6) is over moisture deficits (negative values).

2.4. The linear mixed-effects model (LMM)

Simulated irrigation requirement data were further analysed to establish the dependence on climate, soil and crop type. These irrigation data are derived from repeated-predictions of the same climate-soil-crop combination and hence they may be temporally autocorrelated, potentially, contravening assumptions of independence of data points. Therefore, linear mixed-effects modelling was employed. Linear mixed-effects models (LMMs) are statistical models of continuous outcome variables in which the residuals are normally distributed but may not be independent or have constant variance (West et al., 2014). LMMs have been used in the fields of social science (Duncan et al., 1996), medicine (Beacon and Thompson, 1996) and agriculture (Green et al., 1998) but they appear less in the ecological literature. The use of mixed-effects modelling to analyse the irrigation data allowed us to account for the correlations in irrigation data. Furthermore, it allowed us to quantify the variability in the effects of climate and soil on irrigation requirement between crops by making crop-specific adjustments to the intercept and slope(s) of the linear regression model.

For the development of the optimal LMM model we followed the iterative procedure of model testing and refinement as described by Zuur et al. (2009) and West et al. (2014). As an initial diagnostic, we fitted a regression model

Table 3: Values of the N_m factor in equation 2 calculated by dividing the possible sunshine hours for the latitude of the analogue station by 12.

Month	**Dessel**	**Blindern**	**Malaga**
Jan	0.7	0.56	0.84
Feb	0.83	0.75	0.92
Mar	0.98	0.98	0.99
Apr	1.14	1.21	1.09
May	1.28	1.43	1.17
Jun	1.36	1.55	1.21
Jul	1.33	1.49	1.19
Aug	1.20	1.29	1.13
Sep	1.05	1.08	1.03
Oct	0.89	0.84	0.94
Nov	0.75	0.63	0.86
Dec	0.68	0.49	0.82

using the Generalised Least Square (GLS) approach with climate, soil and their interaction as the main effects. We then tested several LMMs including: (i) random intercept, (ii) random intercept and climate effect associated with crop type and (iii) random intercept and soil effect associated with crop type. The process of building LMMs resulted in a number of competing models for the same data set. We selected between these competing models using hypotheses testing and by comparing the Akaike Information Criteria (AIC) of the alternative models (Akaike, 1973).

The random part of the LMM was optimised by means of likelihood ratio tests. A likelihood ratio (*LR*) was calculated as follows:

$$LR = -2\ln\left(\frac{L_{reduced}}{L_{refrence}}\right) \tag{7}$$

$L_{reduced}$ and $L_{reference}$ are the likelihood function evaluated at the restricted maximum likelihood (REML) estimates of the parameters in the reduced model (excluding the random effect to be tested) and in the reference model (including all random effects). Significance of the respective random effect was tested by referring the *LR* to a χ^2 distribution with the appropriate degrees of freedom (i.e. the number of extra parameters in the reference model relative to the reduced one). If *LR* was sufficiently large and the test was significant (at the 5% level), there was evidence in favour of the reference model and the random effect was considered significant and retained in the model. Otherwise, it was removed from the model.

Next, the fixed part of the LMM was optimised by re-fitting the LMM with the optimised random structure using the maximum likelihood (ML) function and then removing nonsignificant fixed-effects from the LMM.

The best fitting model was then validated by means of diagnostic plots of model residuals. All models were fitted using the gls and nlme packages in R 3.2.2 software (R Core Team, 2015).

3. Results and discussion

3.1. Climatic analogues

Long-term mean monthly weather variables for the analogue stations at Dessel, Malaga and Blindern are presented in Table 4. According to Köppen-Trewartha climate classification (Belda et al., 2014) these stations qualify as temperate, Mediterranean and continental, respectively. Compared to Dessel, mean annual precipitation in Blindern and Malaga stations is less by 13 and 40%, respectively. Precipitation is almost equally distributed throughout the year under temperate and continental conditions in Dessel and Blindern whereas precipitation under Mediterranean conditions in Malaga is mainly during winter months. Under all climates, ET_0 is characterised by strong seasonality with maximum values recorded during summer months.

Table 4: Mean air temperature (°C), precipitation P (mm) and reference evapotranspiration ET_0 (mm) for the analogue stations over the period from 1979 to 1998.

Month	**Dessel**				**Blindern**				**Malaga**			
	T_{max}	T_{min}	P	ET_0	T_{max}	T_{min}	P	ET_0	T_{max}	T_{min}	P	ET_0
Jan	5.2	-0.6	77	14	-1.1	-6.2	47	10	16.7	7.4	90	66
Feb	6.2	-0.7	55	20	0.0	-6.0	36	13	17.6	7.9	59	71
Mar	10.2	2.1	79	38	3.9	-2.5	54	32	19.5	9.4	41	103
Apr	13.7	3.8	53	60	9.4	1.1	42	61	21.1	10.6	33	123
May	18.3	7.8	64	86	16.3	6.6	46	105	24.1	13.6	22	159
Jun	20.5	11.0	87	90	19.8	10.5	71	115	27.6	17.4	9	183
Jul	22.9	12.8	76	101	22.0	12.6	76	122	30.0	19.9	1	199
Aug	23.0	12.2	65	89	20.4	11.7	97	91	30.4	20.7	7	180
Sep	19.1	9.5	79	52	15.1	7.5	86	51	28.1	18.5	19	135
Oct	14.8	6.6	86	31	9.1	3.5	85	25	23.8	14.4	55	95
Nov	9.3	2.8	75	14	3.1	-1.4	69	11	20.2	11.2	112	67
Dec	6.5	1.2	84	13	-0.1	-5.0	59	9	17.6	8.5	76	63
Annual	14.8	5.7	880	608	9.8	2.7	764	646	23.1	13.3	526	1444

3.2. AquaCrop irrigation estimates

Summary statistics for the irrigation requirements simulated using AquaCrop for the 27 scenarios (i.e. all combinations of climate, soil and crop type) are presented in Table 5. Across all simulated scenarios, annual irrigation requirement ranged between 66 and 444 mm y^{-1}.

Table 5: Summary statistics of the annual irrigation requirement (mm y^{-1}) for all simulated scenarios between 1981 and 1996. The standard deviation of the mean is given in the parentheses.

Climate	Soil	Crop	Min	Median	Max	Mean (SD)
Temperate	P	Beans	98	153	217	158 (38)
		Potato	120	228	327	213 (56)
		Winter wheat	66	123	318	131 (61)
	S	Beans	116	165	233	174 (36)
		Potato	164	252	354	248 (53)
		Winter wheat	118	159	321	169 (52)
	Z	Beans	124	174	237	181 (36)
		Potato	180	274	372	267 (55)
		Winter wheat	139	189	343	199 (51)
Continental	P	Beans	143	225	295	221 (39)
		Potato	164	290	374	284 (50)
		Winter wheat	122	266	344	250 (59)
	S	Beans	160	242	310	239 (39)
		Potato	222	339	412	330 (47)
		Winter wheat	167	306	394	300 (51)
	Z	Beans	164	249	306	247 (37)
		Potato	256	362	444	357 (45)
		Winter wheat	232	365	443	359 (48)
Mediterranean	P	Beans	318	339	377	339 (15)
		Potato	317	355	391	354 (21)
		Spring wheat	121	235	384	249 (78)
	S	Beans	319	344	370	343 (13)
		Potato	340	377	418	373 (23)
		Spring wheat	160	280	402	280 (69)
	Z	Beans	318	339	368	338 (14)
		Potato	354	380	424	384 (21)
		Spring wheat	175	311	414	307 (68)

AquaCrop values were validated by means of comparison with measured values reported in the literature for similar crops and environmental conditions. Whereas there are data available for dry and arid conditions, actual irrigation data for temperate and continental conditions are scarce. This is probably because irrigation under cool and wet conditions is not a common practice.

3.2.1. Comparison with observed data

In general, AquaCrop irrigation values are in the range of published data (Table 6). The wider range of actual irrigation rates reported in the literature might be attributable to the greater range of environmental conditions and irrigation management in the field compared with the simulated conditions.

Table 6: Comparison of AquaCrop simulated crop irrigation requirement values and measured values reported in the literature from field studies.

Climate	Crop	AquaCrop	Measured	Reference
Temperate	Beans	98-237	20-408	Vanuytrecht (2013)
				Kuşçu et al. (2009)
	Potato	120-372	0-300	Janssens and Coussement (2014)
				Vanuytrecht (2013)
				Ahmadi et al. (2011)
				Shahnazari et al. (2008)
Mediterranean	Beans	306-337	157-338	Bonachela et al. (2006)
				Sezen and Yazar (2006)
	Potato	317-424	4-477	Ferreira and Carr (2002)
	Wheat	121-414	95-396	Cossani et al. (2012)
				Albrizio et al. (2010)
				Sezen et al. (2005)
				Oweis et al. (2000)

A wider range of irrigation methods and criteria are applied under field conditions compared to those considered here, such as supplemental or deficit irrigation management. For instance, supplemental irrigation uses precipitation as the source of water for the crop and small amounts of water are added to essentially rainfed crops during times when rainfall fails to provide sufficient moisture for normal plant growth, in order to improve and stabilise yields. Deficit irrigation aims to improve water use efficiency by eliminating irrigation that has a little impact on yield. The resulting yield reduction may be small compared with the benefits gained by diverting the unused water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

Irrigation rates applied under such irrigation management schemes may not be appropriate as they would not comply with the conservatism inherent in radiological impact assessments which aims to ensure that, given the assessment uncertainty, the regulatory limits will not be exceeded (ICRP, 1998).

3.2.2. Comparison with the empirical methods

In addition to comparing AquaCrop calculated irrigation requirements to measured irrigation values, we also compared our AquaCrop estimates with those obtained from estimation methods of Thornthwaite and Becker (Table 7). The order of climates with respect to irrigation requirements was consistent between Thornthwaite and AquaCrop methods; estimates from the Becker method, however, did not follow this order (irrigation requirements for the continental climate were the lowest).

Table 7: Mean annual irrigation requirements (mm y^{-1}) estimated using three different methods.

Climate	AquaCrop	Thornthwaite	Becker
Temperate	66-372	93-284	18-181
Mediterranean	121-424	195-405	149-352
Continental	122-444	86-291	0-147

Both Thornthwaite and Becker's estimates were at the lower end of the range of AquaCrop estimates and the values reported in the literature (Table 6), especially for the temperate conditions. Thornthwaite performs slightly better for cold conditions (based on the measured values in Table 6). The strong correspondence between Thornthwaite and Becker methods (as Fig. 3 indicates) is probably due to temperature being the main calculation variable in these methods.

Thornthwaite is an approximate approach which can be used together with precipitation to give an indication of monthly, seasonal and annual water balances. However, Thornthwaite method is not valid for climates other than those similar to that of the area where it was developed, i.e. the eastern USA (Shaw, 1998). Moreover, Thornthwaite values tended to overestimate the potential evapotranspiration compared with estimates from the Penman-Montieth model embedded in AquaCrop (results not shown). This is consistent with the observation of Shaw (1998) who noted that Thornthwaite estimates tend to exaggerate the potential evaporation compared with estimates from Penman method. This is particularly marked in the summer months with the high temperatures having a dominant effect in the Thornthwaite computation, whereas the Penman estimate takes into consideration other meteorological factors. Nevertheless, annual irrigation requirements calculated with Thornthwaite were, on average, 15% lower than those predicted by AquaCrop. Becker estimates appear to be systematically lower than those from Thornthwaite (by about 44%) and AquaCrop (by about 52%).

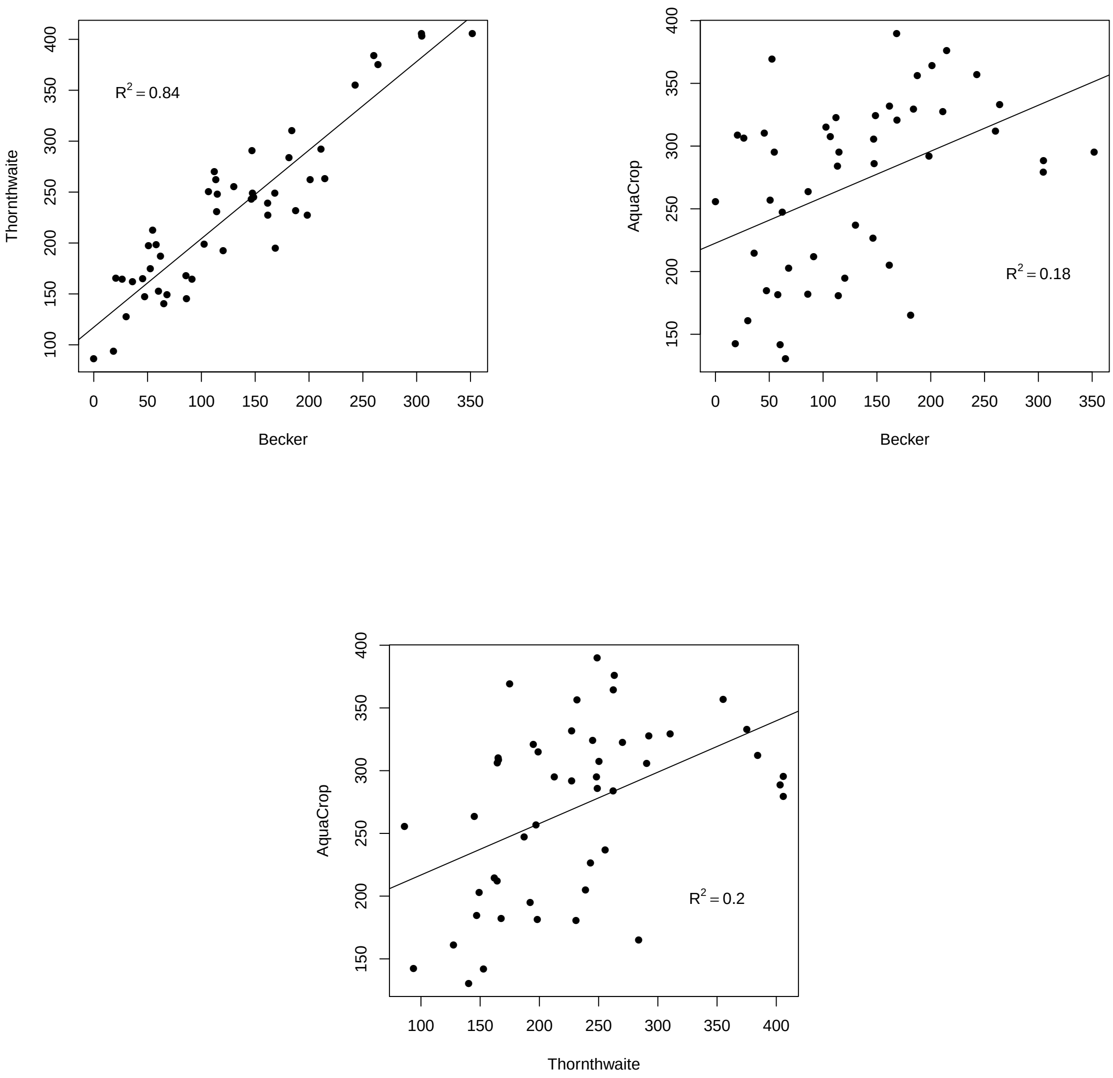

Figure 3: Correspondence between Thornthwaite, Becker and AquaCrop methods for estimating irrigation requirement

These comparisons suggest that in spite of its key role, estimates based solely on air temperature and, in case of Thornthwaite, day light hours may not be sufficiently representative of crop irrigation requirements. Our AquaCrop estimates are systematically higher than those from Thornthwaite and Becker methods, this may be attributable to the irrigation strategy adopted in our work. We used AquaCrop to simulate growth under full irrigation (irrigation was started at 30% depletion of RAW throughout the crop life cycle). This approach provides a theoretical maximum irrigation requirement (Wriedt et al., 2009). Ideally, the percentage of RAW depletion differs among crops and should be varied with crop growth stages. Irrigation at 30% depletion of readily available water (RAW) may be required up to the time of full canopy development, afterwards, irrigation could be applied at a much lower threshold (e.g. 80-90% of RAW) since stomatal closure and canopy senescence are more resistant to water stress (Hsiao, T. personal communication). Our simulated irrigation rates are maximum and intended to be consistent with the conservative approach to safety assessment of waste disposal facilities.

3.2.3. The optimal LMM parametrisation

Simulated irrigation requirement for the 27 scenarios between 1981 and 1996 reveals consistent trends of increasing irrigation requirement as the climate changes from temperate to continental to Mediterranean and as soil type changes from P to S to Z (Fig. 4). Irrigation requirements for some of the simulated scenarios (e.g. continental climate) show a substantial year-to-year variation whereas for other scenarios (e.g. Mediterranean) the annual variation was smaller. The maximum variation in irrigation requirement is between climates whereas the minimum variation is between soils. There is also a noticeable variation in irrigation requirement between crops.

There was sufficient evidence to support the application of mixed effects modelling to analyse the simulated irrigation requirement data. Fig. 5 shows a discernible association between climate type and crop irrigation requirement. Fig. 6 shows the relationship between soil type and irrigation requirement; increasing with the sand content of the soil. The potato crop had the highest irrigation requirements amongst the simulated crops (Fig. 7).

Since we have time series of irrigation data, it is possible that for a given scenario the irrigation requirement in one year is dependent on the irrigation requirement in the previous year. Hence we should take this temporal autocorrelation in the data into consideration during the analysis.

There seems to be a trend in irrigation over time for some scenarios (e.g. wheat under Mediterranean climate) (Fig. 8). The significance of autocorrelation in the data was tested at different time lags. The statical tests showed that autocorrelation was significant ($p < 5\%$ level) in one out of the 27 simulated scenarios (wheat growing on S soil under temperate climate). Therefore, autocorrelation was not considered further in the analysis.

We derived the optimal LMM parametrisation following the procedure described in Section 2.4. The optimal LMM included climate and soil as fixed factors and crop as a random factor:

$$\mathrm{IR}_{it} = \beta_0 + \beta_1 \mathrm{Mdtr} + \beta_2 \mathrm{Cntn} + \beta_3 \mathrm{S} + \beta_4 \mathrm{Z} + b_{0i} + b_{1i} + \varepsilon_{it} \quad (8)$$

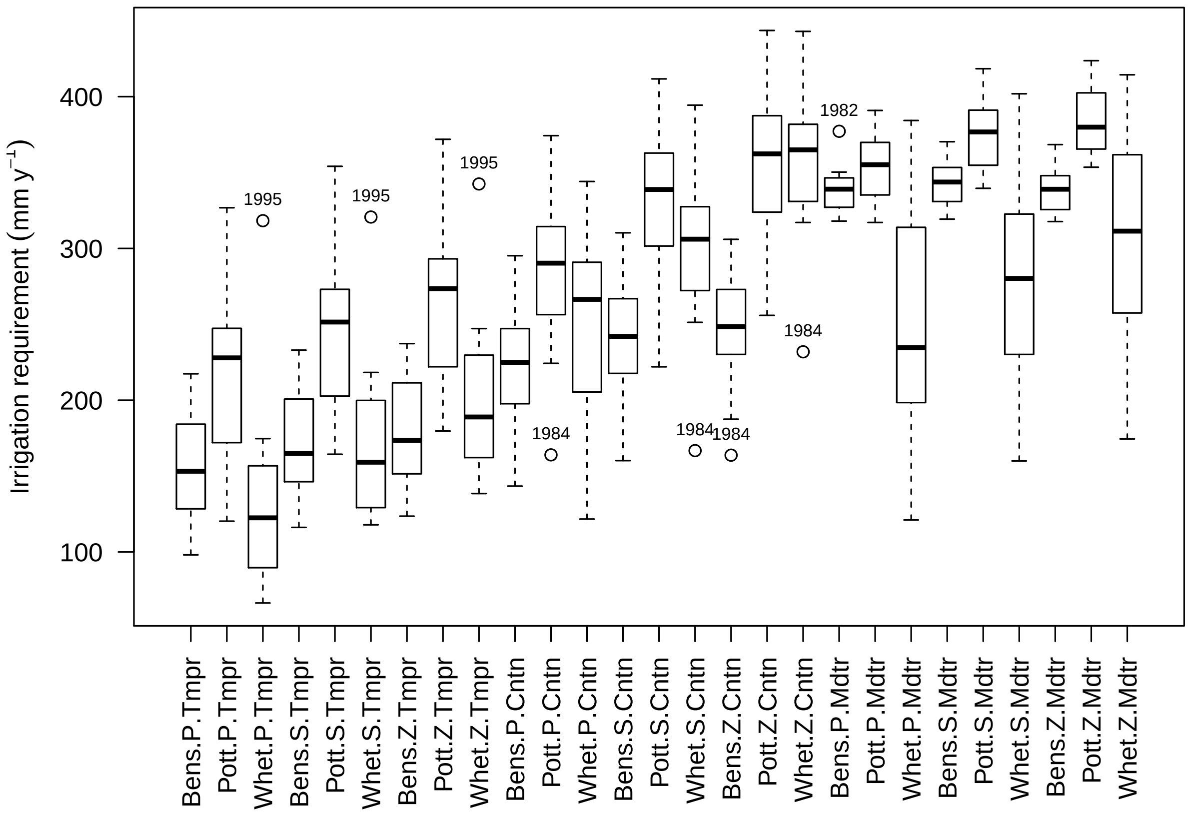

Figure 4: Irrigation requirement for the 27 simulation scenarios showing a clear trend of increasing irrigation requirement as climate changes from temperate (Tmpr) through continental (Cntn) to Mediterranean (Mdtr). The box-and-whisker plots represent the distribution of the simulated irrigation requirements between 1981 and 1996: the thick horizontal line is the median, edges of the box are the upper and lower quartiles, the dashed vertical lines are the whiskers and the open circles are the outliers.

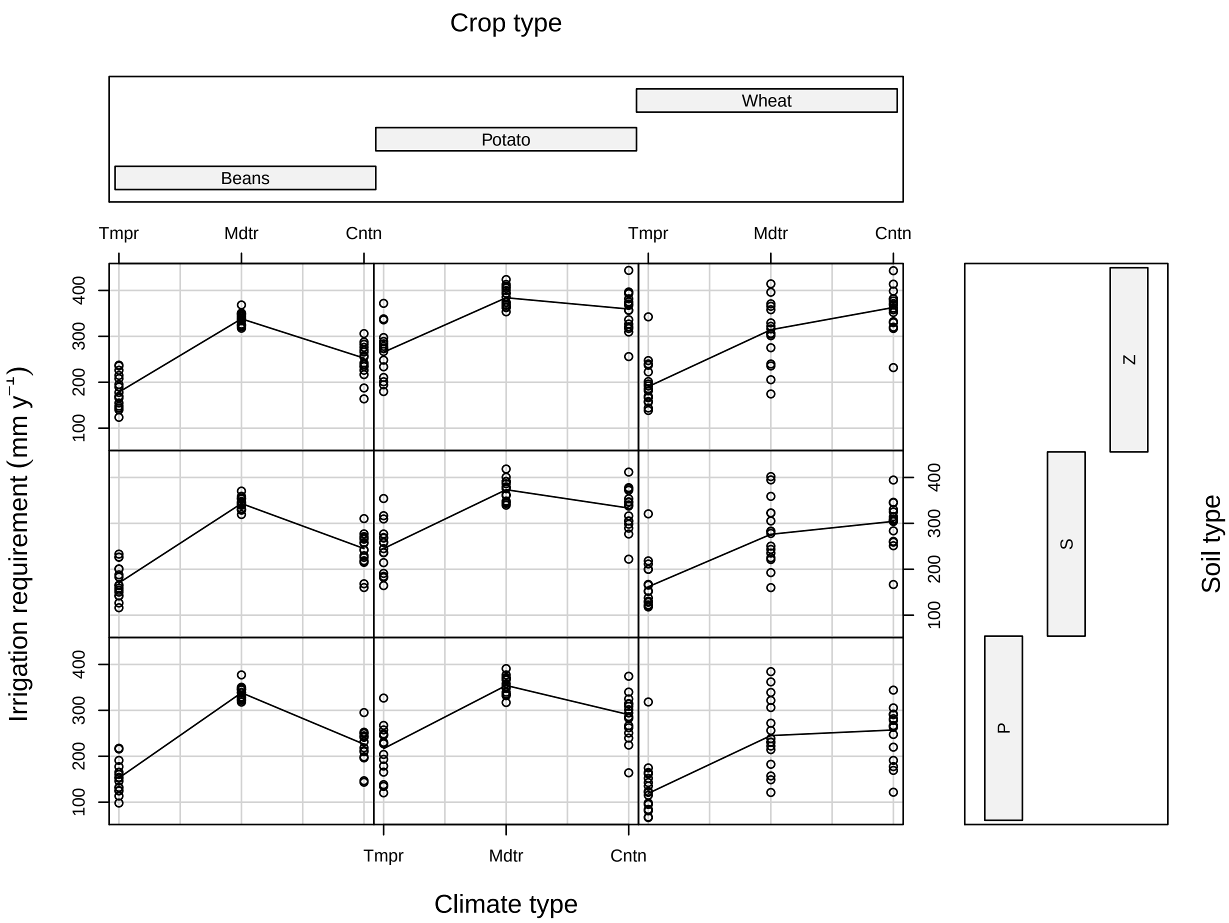

Figure 5: A coplot of the irrigation requirement versus climate type conditional on soil and crop type.

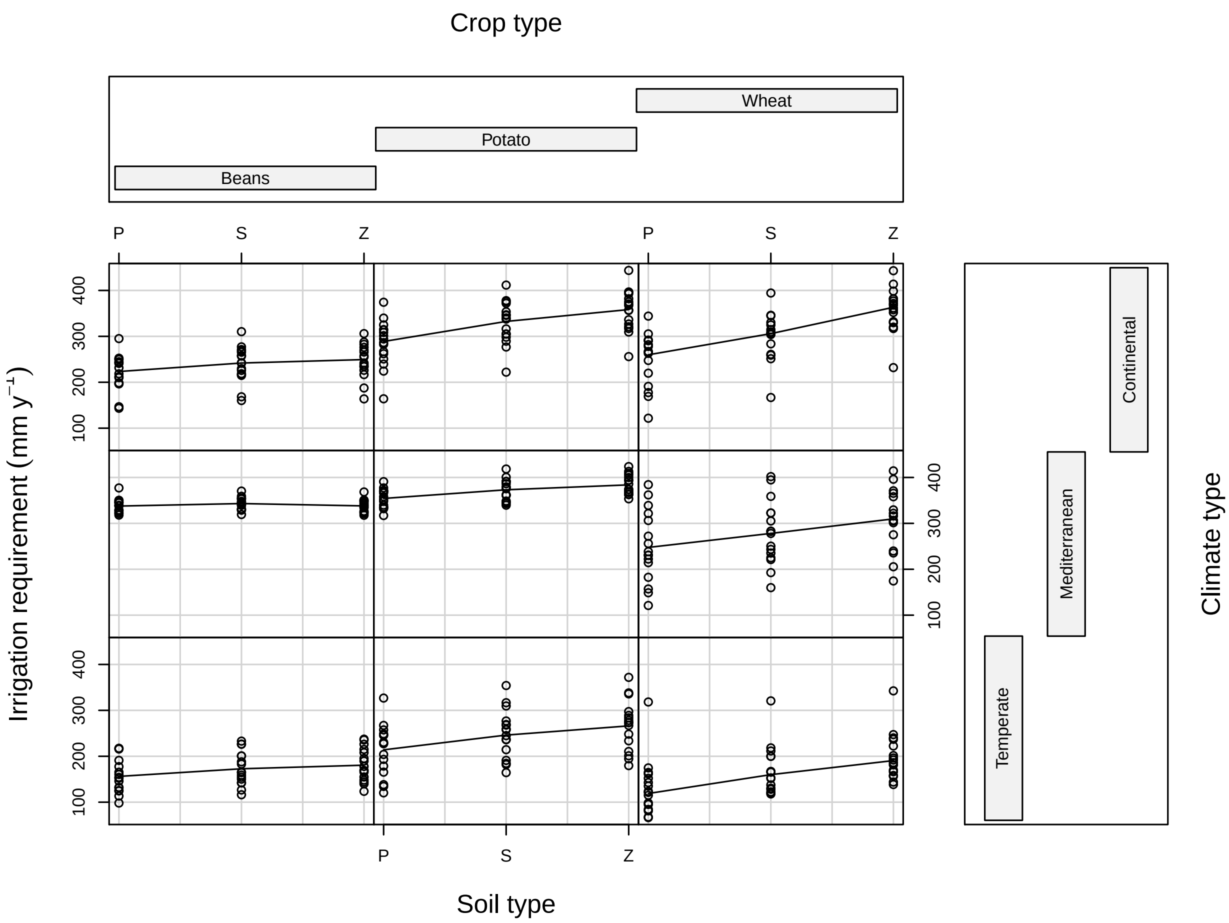

Figure 6: A coplot of the irrigation requirement versus soil type conditional on climate and crop type.

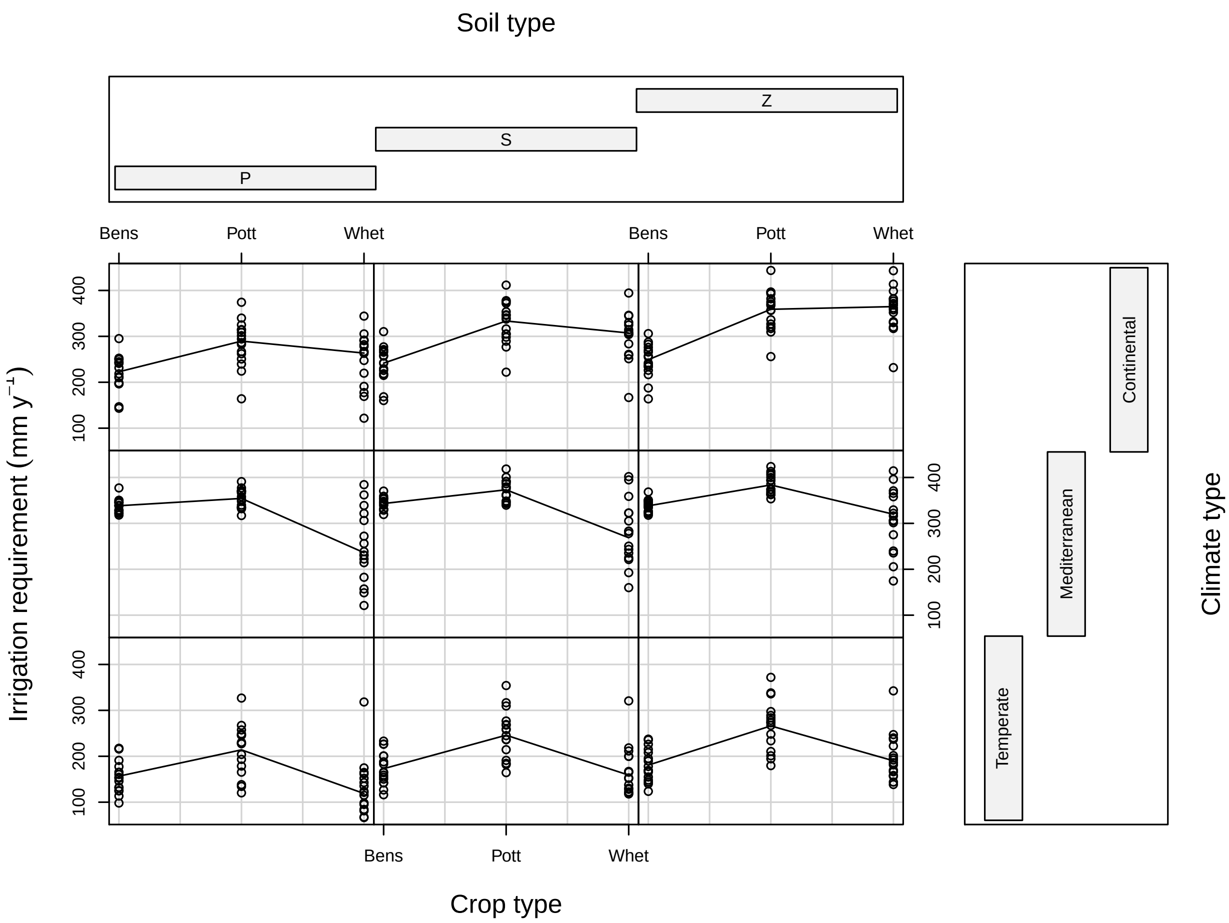

Figure 7: A coplot of the irrigation requirement versus crop type conditional on climate and soil type.

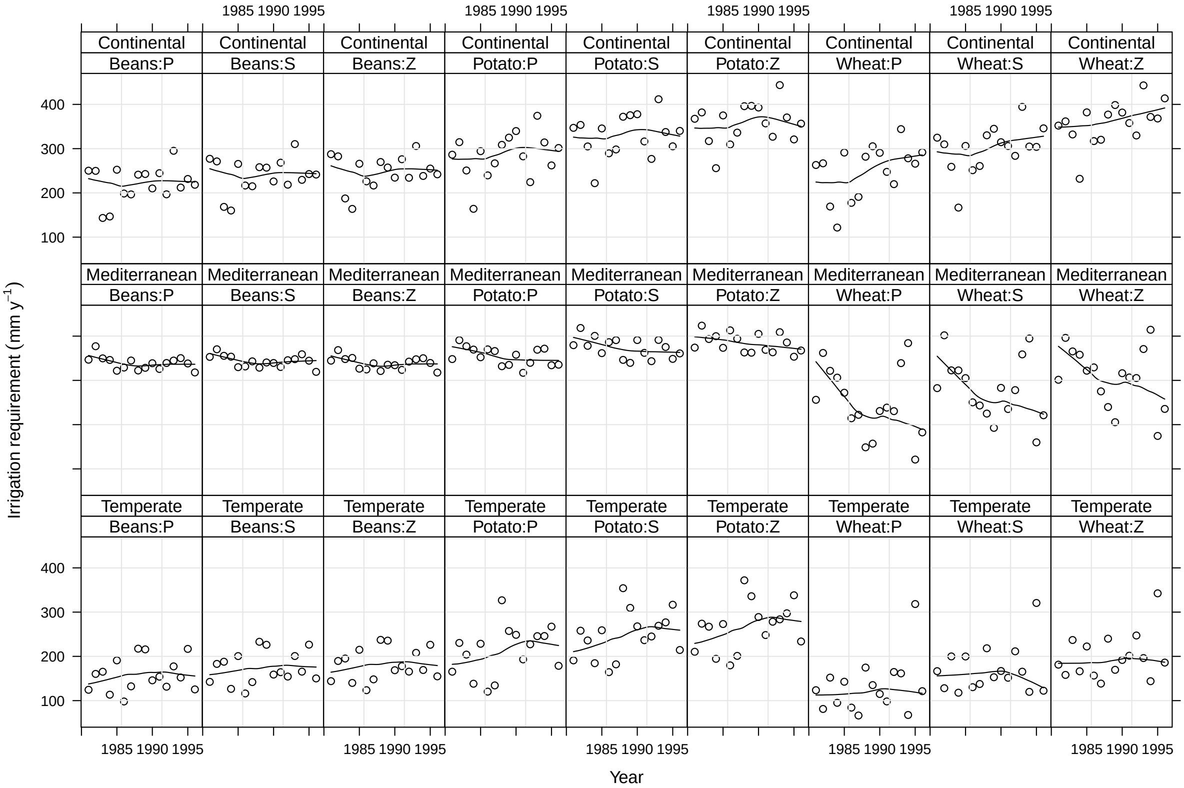

Figure 8: Patterns over time in irrigation requirement simulated using AquaCrop for all scenarios.

where IR_{it} denotes the irrigation requirement (mm y^{-1}) for crop i in year t, β_0 represents the expected value of IR_{it} for the baseline scenario (i.e. temperate climate and P soil), $\beta_{1,2}$ represent the effects of Mediterranean and continental climates vs. the baseline, respectively, $\beta_{3,4}$ represent the effects of S and Z soils vs. P soil, respectively. The terms b_{0i} and b_{1i} are the random deviations for crop i from the expected irrigation requirement β_0 and from the relationships described by $\beta_{1,2}$. The terms b_{0i} and b_{1i} are assumed to follow a bivariate normal distribution:

$$\begin{pmatrix} b_{0i} \\ b_{1i} \end{pmatrix} \sim \mathcal{N}(\mathbf{0}, \mathbf{D}) \quad \text{where} \quad \mathbf{D} = \begin{pmatrix} \sigma^2_{\text{Crop}} & 0 & 0 \\ 0 & \sigma^2_{\text{Mdtr}} & 0 \\ 0 & 0 & \sigma^2_{\text{Cntn}} \end{pmatrix} \tag{9}$$

The parameters in **D** are given in Table 8. The specification of **D** implies that there is no relationship between crop irrigation requirement under the baseline scenario and its response to climate change. This is justified on the basis of values in Table 5 and patterns in Fig. 8. For instance, green beans have a lower irrigation requirement than potato under baseline scenario but the increase in its irrigation requirement due to climate change is more pronounced.

Table 8: Estimates, standard errors, 95% confidence intervals of the fixed-and random-effect parameters and the AIC of the LMM (8). n.c. not computed since the sampling distribution of variance estimates is generally strongly asymmetric and standard errors may be a poor characterisation of the uncertainty.

Parameter	**Estimate**	**Standard error**	**95% Confidence interval**	
			Lower bound	**Upper bound**
β_0 (Intercept)	168	25	119	216
β_1 (Mdtr vs. Tmpr)	137	18	102	171
β_2 (Cntn vs. Tmpr)	94	22	50	138
β_3 (S vs. P)	29	6	18	40
β_4 (Z vs. P)	49	6	38	60
σ_{Crop}	42	n.c.	15	114
σ_{Mdtr}	29	n.c.	10	86
σ_{Cntn}	38	n.c.	13	107
σ	48	n.c.	44	51
AIC	4570.2			

3.3. Climate effect on irrigation requirement

The optimal LMM suggests a highly significant effect of climate on irrigation requirement ($LR = 17.29$, $p = .0002$). Crops growing under Mediterranean and continental conditions are expected to require 82 and 56% more irrigation than what they require under temperate conditions. The strong effect of climate on irrigation requirement is expected given the differences in temperature, precipitation and evapotranspiration between the climates. Rapid accumulation of heat under Mediterranean conditions accelerated crop development and shortened the growing seasons relative to temperate and continental conditions. Nevertheless, the high precipitation deficit (i.e. cumulative negative difference between precipitation and reference evapotranspiration) under this climate resulted in substantial depletion of soil water and irrigation was required to maintain the root zone at field capacity. For instance, even though the simulated growing season of spring wheat is shorter than the season of winter wheat by a maximum of 186 days, the precipitation deficit during its growing season is 20 and 100% higher, respectively, than the deficit during winter wheat season under continental and temperate conditions. This is likely to result in more intense irrigation requirement for the spring variety.

This interaction between climatic conditions and crop development may have significant implications when estimating irrigation requirements under changing climate for radiological impact assessments. A predefined, fixed growing season length could lead to over- or underestimation of crop irrigation requirements (depending on which climate is selected as a baseline).

The large residual variance (σ) possibly indicates a strong effect of annual variation in climatic conditions on irrigation requirements.

3.4. Soil effect on irrigation requirement

The main soil effects (S vs. P and Z vs. P) are highly significant ($LR = 70.87$, $p < .0001$) as indicated by the LMM. Changing the soil type from light sand loam (P) to loamy sand (S) and sand (Z) increased the expected irrigation requirements by 17 and 30%, respectively. This change in irrigation due to soil type change is smaller than that predicted by the LMM for the climate change scenarios.

In general, crops growing on the sandy Z soil were simulated to require the highest amount of irrigation. Sandy soils are highly permeability and have a lower water holding capacity compared to loamy sand, S type, and light sand loam, P type, soils. These properties are reflected in the hydraulic characteristics of these soils. For instance, the total available water held in the soil between field capacity and permanent wilting point for the sandy soil is (33 mm m^{-1}) 47% and 28%, respectively, of the total available water for loamy sand (S) and light sand loam (P) soils which have 70 and 117 mm m^{-1} of total available water, respectively. The high K_S value for the sandy Z soil indicates rapid drainage (loss) of root zone water to the subsoil. Soil texture would also affect the magnitude of capillary rise (i.e. upward movement of water) from a shallow groundwater into the root zone. When groundwater is relatively shallow, capillary rise would supply crops with part of their water needs for growth reducing the amount of irrigation requirement. Even though AquaCrop has a module to simulate capillary rise of groundwater to the root zone, we decided not to consider this component of the water balance equation in order to be consistent with the conservative approach we adopted in our study.

3.5. *Crop effect on irrigation requirement*

We included crop as a random factor in the LMM. This is justified on the basis that the crops in our study are a subsample from a wide range of crops grown in the study region. Treating crop as a random factor allows us generalise the results of the analysis (by estimating variances instead of fixed-estimates regression coefficients) and to assess the variation in irrigation requirement between crops under baseline and climate change scenarios.

The optimal LMM specification implies that the irrigation requirement of individual crops under the baseline scenario would deviate from the estimated mean (i.e. β_0). It also implies that the response of individual crops to climate change with respect to their irrigation requirement would deviate from the estimated mean change (i.e. $\beta_{1,2}$). These deviations follow normal distributions characterised by the variance parameters ($\sigma_{Crop,\ Cntn,\ Mdtr}$) in Table 8. The irrigation requirements of the individual crops estimated using the expected values of the random effects given the simulate irrigation data are presented in Table 9.

The variance parameter values indicate a large variation in irrigation requirement between crops under the baseline and climate change scenarios. The largest variation is estimated for the baseline scenario and decreases as climate changes to continental and Mediterranean type (where essentially all the water necessary for crop growth must be provided by irrigation). This trend is consistent with the spread in the simulated irrigation data in Fig. 4.

Table 9: Crop-specific irrigation requirements under the baseline and climate change scenarios estimated by the LMM.

Crop	Tmpr: $\beta_0 + b_{0i}$	Mdtr vs. Tmpr: $\beta_1 + b_{1i}$	Cntn vs. Tmpr: $\beta_2 + b_{1i}$
Beans	146	166	64
Potato	215	130	83
Wheat	141	113	135

Differences in irrigation requirement between crops growing under the same environmental conditions might be partially explained by differences between their characteristics. Irrigation is closely related to the amount of water transpired by crops which is a function, amongst other factors, of the crop transpiration coefficient. This coefficient varies with crop characteristics such as albedo, crop height, aerodynamic properties and leaf and stomata properties and canopy cover.

Even though they have similar irrigation requirements under the temperate conditions, beans and wheat crops differ in the magnitude of their response to climate change. The increase in the irrigation requirement of wheat is lower than that of beans under Mediterranean conditions. This trend is reversed under the continental conditions. We recall that spring wheat, which is growing under the Mediterranean climate, grows over winter and through spring whereas beans grow over the dry summer period. This has possibly contributed to the lower increase in wheat irrigation requirement predicted by the LMM. This trend is reversed under the continental conditions probably due to the higher precipitation deficit during the growing season of winter wheat compared to the beans crop.

4. Conclusions

Using meteorological data from analogue temperate, Mediterranean and continental stations and the crop growth AquaCrop model we estimated irrigation requirements for some major crop categories under a range of environmental conditions for use in radiological impact assessments. The annual irrigation requirements simulated with AquaCrop for the range of climate, soil and crop types considered in our study varied between 66 and 444 mm y^{-1}.

Comparisons between AquaCrop and other empirical methods proposed for use in radiological impact assessments showed poor correlation between the different approaches. Irrigation estimates from all models were within the range of measured values reported in the literature. The estimates from the AquaCrop, however, may be more appropriate for conservative radiological assessments than those from the empirical methods.

Linear mixed-effects modelling of the simulated irrigation data revealed strong and significant climate and soil effects on simulated irrigation requirement. Overall, simulated irrigation requirements increased as climate changed from present-day temperate to Mediterranean and continental conditions with the maximum increase of 80% associated with transition toward Mediterranean conditions. Irrigation requirements increased with the soil sand content. The maximum increase (30%) was associated with the change from light sand loam to sandy soils. The soil effect was unaffected by the climate type as indicated by the insignificant climate by soil interaction term in the LMM.

The simulation results indicated strong interactions between crop phenology and climatic conditions. Rapid heat accumulation under Mediterranean conditions shortened the length of crop life cycle which counteracted the positive effect of higher precipitation deficit on irrigation. This interaction needs to be taken into account when estimating irrigation requirements, adjusting the length of the growing season depending on climatic conditions.

The irrigation requirements presented in our study are a useful alternative when measured irrigation data are lacking for use in radiological impact assessments. And to the best of our knowledge, this is one of the most comprehensive analysis of irrigation data in the context of radiological assessment currently available.

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Appendix: AquaCrop parameter values used in simulation runs

Table 10: Conservative and non-conservative AquaCrop parameters calibrated for the temperate conditions by Vanuytrecht (2013) and used in our study to simulate growth under maritime and continental temperate conditions (and for the green beans crop under Mediterranean conditions). For potato and wheat runs under Mediterranean conditions the default AquaCrop parameter values previously calibrated on field observations from warm conditions were used.

Parameter	**Unit**	**Green beans**	**Potato**	**Winter wheat**
Anaerobiotic point below saturation limiting aeration	vol%	5	5	5
Soil surface covered by an individual seedling at 90% emergence	cm^2	5	20	0.75
Maximum canopy cover	-	1.0	1.0	0.92
Increase in canopy cover	Fraction GDD^{-1}	0.014	0.009	0.008
Decrease in canopy cover	Fraction GDD^{-1}	0.002	0.008	0.008
Nr. of plants per hectare	1000 plants ha^{-1}	30	45	300
Crop determinancy linked with flowering	-	0	0	1
Period from sowing to emergence	GDD	110	120	100
Total ET_0 during stress period to be exceeded before senescence is triggered	mm	0	0	0
Effect of canopy cover in reducing soil evaporation in late season stage	-	60	60	50
Excess of potential fruits	%	-	-	100
Period from sowing to flowering	GDD	450	650	1200
Length of flowering	GDD	300	0	180
Ratio of water productivity normalised for ET_0 and CO_2 during yield formation	%	100	100	100
Period of harvest index building-up during yield formation	GDD	1100	400	550
Allowable maximum increase of specified harvest index	%	60	5	15
Coefficient describing negative impact on harvest index of stomatal closure during yield formation	-	10	3	7
Reference harvest index	%	32	90	55
Possible increase of harvest index due to water stress before flowering	%	2	2	5

Continued on next page

Table 10 – continued from previous page

Parameter	Unit	Green beans	Potato	Winter wheat
Coefficient describing positive impact on harvest index of restricted vegetative growth during yield formation	-	0.5	-	10
Crop coefficient when canopy is complete but prior to senescence	-	1.1	1.1	1.1
Decline in the crop coefficient due to ageing, nitrogen deficiency, etc.	% day^{-1}	0.15	0.15	0.15
Total length of crop cycle (from sowing to maturity)	GDD	870	1850	1900
Lower threshold for soil water depletion factor for canopy expansion	-	0.55	0.60	0.65
Shape factor for water stress coefficient for canopy expansion	-	3	3	5
Upper threshold for soil water depletion factor for canopy expansion	-	0.05	0.20	0.20
Minimum air temperature below which pollination starts to fail	°C	-	-	5
Maximum air temperature above which pollination starts to fail	°C	-	-	35
Upper threshold for soil water depletion factor for pollination	-	0.92	0.80	0.85
Upper threshold for soil water depletion factor for canopy senescence	-	0.70	0.70	0.70
Shape factor for water stress coefficient for canopy senescence	-	3	3	2.5
Upper threshold for soil water depletion fraction for stomatal control	-	0.40	0.55	0.65
Shape factor for water stress coefficient for stomatal control	-	3	3	2.5
Period from sowing to maximum rooting depth	GDD	650	650	1200
Maximum root water extraction in bottom quarter of root zone	$m^3m^{-3}day^{-1}$	0.01	0.022	0.01
Maximum root water extraction in top quarter of root zone	$m^3m^{-3}day^{-1}$	0.04	0.088	0.035
Minimum effective rooting depth	m	0.3	0.3	0.3
Shape factor describing root zone expansion	-	15	15	15
Maximum effective rooting depth	m	0.6	0.6	1.5
Period from sowing to senescence	GDD	850	1550	1550
Minimum growing degrees required for full biomass production	°C day^{-1}	14	8	8

Continued on next page

Table 10 – continued from previous page

Parameter	**Unit**	**Green beans**	**Potato**	**Winter wheat**
Base temperature below which crop development does not progress	°C	6	2	2
Upper temperature above which crop development no longer increases with an increase in temperature	°C	30	26	26
Crop type: 2 = fruit/grain, 3 = root/tuber	-	2	3	2
Water productivity normalised for ET_0 and CO_2	g m^{-2}	15	18.5	18.5

1. Reviewer #1:

1.1 The abstract could be strengthened to reflect the relevance of the modelling for generic dose assessments and as a means of obtaining irrigation requirement for a specific site under alternate climate conditions.

We thank the reviewer for highlighting this rather important conclusion of the present work. We have added this to the abstract.

1.2 In the comparison of AquaCrop and the empirical methods and in the LMM analysis the influence of soil properties clearly seen. More emphasis could be placed on this result.

We thank the reviewer for highlighting this important conclusion of the present work. We have emphasised this conclusion in the abstract.

1.3 At various points in the text reference is made to "climate change" with the implication that this is modelled as a process rather than a feature of the models, ie, that the model includes the transition from one state to another (process). In fact the numerical results in the paper deal with irrigation requirements for specified conditions (feature). The use of AquaCrop and the LMM result should be able to deal with transitions but this has not been carried out. In some places the text is misleading.

We agree with the reviewer that in our paper climate change was a feature not a process. Therefore, we clearly stated in the introduction section of the paper that the simulated climate change scenarios were obtained from a previous study (where climate change was indeed treated as a process). We made reference to the BIOCLIM project where specialised climate models were applied to project future climate scenarios over certain parts of Europe and to the study of Van Geet et al. (2012) where the results of the BIOCLIM project were extrapolated for the Belgian context.

1.4 Page 3: The acronym LMM first appears on page 3 but the full expression linear mixed-effect modelling is not included. It should be.

Corrected

1.5 Page 4: In the figure "gs" is used for stomatal conductance, in the figure caption "Gs" is used.

Corrected

1.6 Page 4: "were used in AquaCrop setup" → "were used in the AquaCrop setup"?

Corrected

1.7 Page 7: "Appendix.GDD (growing" → "Appendix. GDD (growing".

Corrected

1.8 Page 7: Parameters in Table 2 should be named, reference to the Appendix is not sufficient.

Parameters are now fully described in the caption of the table

1.9 Page 8: " (please note that the BIOCLIM report relied upon the 1st edition of Shaw's book while we consulted the 3rd edition)." This should be a footnote.

Done

1.10 Page 10: "The use of mixed-effects modelling to analyse the irrigation data allowed us to account for the correlation in irrigation data". "the correlation" → "correlations"?

Changed

1.11 Page 9 - 10: The empirical methods are stated in mathematical form. The LMM expression is stated on page 16. To allow a comparison Equation (8) could be moved here.

Our justification for having eq (8) in the results section rather than in the materials and the methods section (where the equations of the empirical methods are) is that eq (8) is really a result of the analysis process. We could not get to eq(8) without running a full linear mixed-effects modeling. Therefore, we think it is appropriately place under the results section.

1.12 Page 11: "conditions in Malag is mainly during winter months" → "conditions in Malaga is mainly during winter months"

Corrected

1.13 Page 14: "estimates from Becker method" → "estimates from the Becker method"

Corrected

1.14 Page 14: Might the data in Table 7 be more informative as a plot?

We think that Table 7 enables a straightforward quantitative comparison between the irrigation rates estimated with the three methods. A plot does not offer the same function.

1.15 Page 16: "day light hours may not be representative of crop irrigation requirements" → "day light hours may not be sufficiently representative of crop irrigation requirements"

Corrected

1.16 Page 16. Acronym RAW is not defined.

Acronym has been defined

1.17 Page 17: Clearer separation of the different crops would be useful here. Individual plots for the three crop types would help.

We believe that the current graph offers the possibility to compare at a glance the differences in irrigation requirement between crops growing on different soils under different climatic conditions. It also shows a trend of increasing irrigation requirement as climatic conditions change from temperate→continental→Mediterranean.

1.18 Page 24: missing sigmas: "parameters (<sigma>Crop; Cntn; Mdtr) in Table 8." → "parameters (<sigma>Crop; <sigma>Cntn; <sigma>Mdtr) in Table 8."

sigmas in table 8 are not missing

1.19 Looking at the map on page 5 it is clear that Dessel is relatively close to the Atlantic coast. Is there any Maritime influence to the climate there?

Indeed, the Dessel site has a maritime temperate climate. We have highlighted this effect in the caption of Figure 2 in Section 2.2.1

1.20 Discussion of irrigation practices on page 13, 14. In terms of dose assessments the results here express the irrigation requirement of crops. The upper end of the range is, perhaps, more suitable to allow for non-commercial cultivation practices (kitchen garden) where extra irrigation might be added.

We agree with the reviewer that the upper range of the *net irrigation requirement* values reported in our work is suitable for non-commercial cultivation practices. We also believe that they are equally suited for commercial cultivation practices where extra water is often added to the net irrigation requirement to compensate for water losses e.g. during transport, evaporation, etc. In other words, the net irrigation requirement reported in our work might be representative of the *gross irrigation requirement* (i.e. quantity of water to be applied in reality, taking into account water losses) applied in commercial cultivation practices.

1.21 Are the authors recommending the result of the LMM as practical alternative to the application of AquaCrop in order to simulate the irrigation requirement for crops with variant soil types and under different climate conditions?

In principle, a properly parameterised LMM model (using measured irrigation, climate and soil data) can be a practical alternative to AquaCrop for estimating irrigation data for radiological impact assessments. We would then suggest that instead of using classes for climate and soils (as was done in this site-specific study) to use other climate and soil characteristics such as precipitation, reference evapotranspiration, readily available water, etc. to parameterise the LMM. This help avoid subjective classification of climate and soil types as there are few different schemes available in the literature.

2. Reviewer #2:

2.1 "Irrigation data for radiological assessments are scarce". I do not really disagree with this point as explained in the text from line 30-34 but it is somewhat misleading.

We thank the reviewer for his remark, we have modified the highlight to take this remark into account.

2.2 "Data are provided using mechanistic and empirical models". This point is a little unclear, data provided for radioecological models up until now (see highlight 1), data provided in this publication or generally?

We mean data derived in the work presented in this article. We have corrected the highlight to clear any ambiguity

2.3 "Empirical models tended to underestimate irrigation requirements". With this point the authors want to stress the improvements in irrigation requirement accuracy of AquaCrop, one of the main conclusions of the paper. I understand the authors define AquaCrop as a mechanistic model, compared to other models, for example Thornthwaite and Becker. If the authors want to stress this point, it should be explained in the text why the authors see AquaCrop as a mechanistic model compared to the simpler empirical models from section 2.3. Despite its higher complexity, AquaCrop may also be defined as an empirical model, since it also uses measured or reported data for parametrisation.

We agree with the reviewer that even though AquaCrop models plant physiology in more depth than empirical formulae such as Thornthwaite and Becker it is not a fully mechanistic model and it still relies on a number of empirical relationships. In order to avoid confusion about its nature, AquaCrop is now described in the paper as a multi-crop model, meaning it can be applied to different crop species which all share the same mathematical representation of the growth processes.

2.4 in my opinion the statement that the "Empirical models tended to underestimate irrigation requirements" and stated in the conclusions (line 367-369) is not backed by the results shown in table 6 and 7. In the comparison between measured, Thornthwaite, Becker and AquaCrop, it is shown that the Thornthwaite and Becker results are lower than AquaCrop results, while all are within reasonable range of the measured values from the literature. Lower results compared to AquaCrop do not mean "underestimate" or wrong. That AquaCrop shows higher results and may thus be more appropriate for a conservative approach (line 266-268) is a different conclusion and may fit better here and in the conclusion section.

We agree with the reviewer that the Thornthwaite and Becker equations did not produce wrong estimates of the irrigation requirement. We also agree that all values were within a reasonable range of the measured values reported in the literature. Nevertheless, comparing the ranges of measured values in Table 6 and the ranges of values simulated with Thornthwaite and Becker in Table 7 shows that the later estimates are more towards the lower end of the range of measured values. This is particularly the case for the method of Becker. Nonetheless, we have modified our highlights, abstract and conclusions to reinforce the conclusion that the estimates from AquaCrop may be more appropriate for conservative radiological assessments.

2.5 Page 4: The resolution of Figure 1 is blurry. In the figure text the closing bracket of "different water stress response functions)." has no corresponding opening bracket.

We apologise for the quality of the figure. It was copied from the original publication of Steduto et al 2009.

2.6 Page 6, line 118: Opening bracket " (generally applicable..." without corresponding closing bracket.

Corrected

2.7 Page 7: In the text for Table 2 missing space after the full stop in "the Appendix.GDD (growing degree days) is a measure"

Corrected

2.8 Page 11 Table 4 and Page 12, Table 5: It is unclear what the irrigation values (min, max, median, mean(sd)) in Table 5 show. Do they reflect the results from different annual precipitations between 1981 and 1996 as stated in the Table 5 text and from line 272-275, or the AquaCrop results for the different months with the climate parameters given in table 4?

The irrigation data in Table 5 reflect the AquaCrop results of the annual irrigation requirement between 1981 and 1996. They were calculated using *daily* values of weather variables between the period 1979 and 1998.

Are the values in Table 4 the means of the annual values for this time period, or the means of the daily values for this month?

Means of the daily values for the month

Are the values given in Table 4 the average of different annual precipitations between 1979 and 1998?

Monthly precipitation averaged over the period 1979 and 1998

Do they compare low precipitation years with high precipitation years, or low precipitation months with high precipitation months?

Low vs. high precipitation months

In addition to this, the time period of table 4 (1979-1998) is different compared to the time period in table 5 (1981-1996).

The weather data for the period between 1979 and 1980 were used to warm up the AquaCrop model, i.e. to wear off the effect of initial simulation conditions (e.g. initial soil moisture profile) on the outputs.

2.9 Page 13 and 14: It may be good to combine Tables 6 and 7 to make it more convenient to compare the measured values to the Thornthwaite and Becker methods.

We prefer to keep the tables separated since they serve two different purposes. Table 6 compared data for specific crops under specific climates whereas Table 7 compares data for specific climates ignoring the crop effect (since Thornthwaite and Becker methods' estimates are crop independent). In fact, if we were to have all data (i.e. measured and modelled) in one, this would lead the reader to believe that we are comparing modelled and observed data representative of *all crops* grown under the specified climates. This, in our opinion, is misleading since we're comparing data for specific crops i.e. those included in the study.

2.10 Page 22 Line 296: it should be "For instance, green beans have a lower irrigation requirement than potatoes…"

Corrected

2.11 Page 22. In the table 8 text it should be " random-effect" not "ranodm-effect"

Corrected

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