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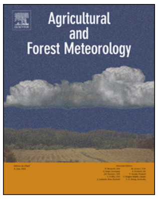

The combined effect of elevation and meteorology on potato crop dynamics: a 10-year study in the Gamo Highlands, Ethiopia

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ABSTRACT

Potato (*Solanum tuberosum* L.) is an important crop in the Gamo Highlands in Ethiopia. The region is characterised by a complex topography with large inter-annual weather variations, where potatoes grow in a range of altitudes between 1,600 and 3,200 m above sea level (a.s.l.). Traditional large-scale crop modelling studies only crudely represent the effect of complex topography, misrepresenting spatial variability in meteorology and potato growth in the region. Here, we investigate how weather influenced by topography affects crop growth.

We used the Weather Research and Forecasting (WRF) model to simulate weather in relation to topography in coarse (54 km × 54 km) and fine (2 km × 2 km) resolution domains. The first has a resolution similar to those used by large-scale crop modelling studies that only crudely resolve the horizontal and vertical spatial effects of topography. The second realistically represents the most important topographical variations. The weather variables modelled in both the coarse and fine resolution domains are given as input to the GECROS model (Genotype-by-Environment interaction on CROp growth Simulator) to simulate the potato growth. We modelled potato growth from 2001 to 2010 and studied its inter-annual variability. This enabled us to determine for the first time in Ethiopia how variations in weather are linked to crop dynamics as a function of elevation at a fine resolution.

We found that due to its finer representation of topography, weather and crop growth spatio-temporal variations were better represented in the fine than in the coarse resolution domain. The magnitude of crop growth variables such as Leaf Area Index (LAI) and Length of the Growing Season (LGS) obtained with weather from the coarse resolution domain were unrealistically low, hence unacceptable. Nevertheless, the resulting potato yields in the coarse resolution domain were comparable with the yields from the fine resolution domain. We explain this paradoxical finding in terms of a *compensating effect*, as the opposite effects of temperature and precipitation on yield compensated for each other along the major potato growing transect in the Gamo Highlands. These offsetting effects were also dependent on the correct estimations of the LGS, LAI. We conclude that a well-resolved representation of complex topography is crucial to realistically model meteorology and crop physiology in tropical mountainous areas.

1. Introduction

Potato is one of the most rapidly expanding crops in Eastern Africa (Haverkort and Struik, 2015) and is a strategic crop for improving food security in Ethiopia (Abebe et al., 2013; FAO, 2008; Hirpa et al., 2012). Ethiopia has the greatest potential for potato production in Africa (FAO, 2008). In Ethiopia, potato is grown during the *belg*[a] (February–May) and *kirmet* (June–September) seasons, as well as off-season under irrigation. The *belg* crop is the most important one (from the total area cropped with potato, 77% is during the *belg* season) (Tufa, 2013), but

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[a] See seasonal classification in Ethiopia in Table S1.

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the potato yield is significantly dependent on annual weather variations and local weather and soil conditions. Although meteorological conditions are also favourable for potato production during the *kirmet* (*meher* harvest) season, diseases - mainly late blight - are more prevalent than during the *belg* season (Haverkort et al., 2012; Tufa, 2013).

Ethiopia has a complex topography. In southwest Ethiopia, the Gamo Highlands rise up from the lowlands at the bottom of the Great Rift Valley at 1,100 m a.s.l. around Lake Chamo to above 3,500 m a.s.l. at the summit of Mount Guge, a distance of less than 50 km. Potato is cultivated there between 1,500 and 3,200 m a.s.l., where the climate is mild and not too wet. As a result of the complex terrain, large contrasts in weather and climate can be observed (Jury, 2014b). These generate variations in potato growth from the relatively unsuitable lowlands to the highly productive highlands, due to different combinations of adiabatic cooling, orographic lifting, and mountain/valley wind conditions. Because crop dynamics and ultimately yield are highly influenced by weather and climate (Samberg et al., 2010), we hypothesize that the modelling of potato crop dynamics is very sensitive to crucial meteorological crop drivers such as short-wave radiation (SW↓), precipitation and temperature, and their variations along steep elevation gradients.

Current operational crop models such as the EU MARS (Monitoring Agriculture with Remote Sensing) system are driven by coarse resolution data from global weather models and/or interpolated station data (*e.g.*, 0.5° × 0.5°) (Boogaard et al., 2002; de Wit et al., 2010; Hijmans, 2003). In such models, for example, the Gamo Highlands are represented by a smoothed topography, which suggests drier and warmer weather characterised by less variability than in models with fine resolution domains (section 3.1). However, recent studies have shown that numerical weather models require sufficiently high resolution to resolve atmospheric phenomena such as spatial variability in temperature and precipitation driven by complex topography (Hunink et al., 2014; Yarleque et al., 2016; Zhao et al., 2015). Our study furthers these recent efforts, as we investigate the impact of weather model resolution on crop dynamics too in a region characterised by complex orography. While we focus on the Gamo Highlands, our objectives and methods are applicable to other mountainous areas in tropical regions.

This study models the impact of key meteorological crop growth drivers on potato growth at high resolution over the Gamo Highlands. To this end, we combine meteorological and crop dynamics models, which exist in a one-way coupled causal relationship. First, we use the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) to simulate weather during a 10-year period in different resolution domains: a coarse one (54 km × 54 km) covering the Greater Horn of Africa including part of the western Indian Ocean (2,808 km × 2,808 km) and a fine one (2 km × 2 km), covering the Gamo Highlands, an area of 84 km × 84 km (Fig. 2). Second, we systematically analyse the impact of these meteorological inputs on the crop dynamics simulated by the Genotype-by-Environment interaction on CROp growth Simulator (or GECROS model, (Yin and van Laar, 2005), hereafter YL05). Using this method, we attempt to answer the following questions:

1) How do weather and climate vary as a function of local topography, and how does it affect potato crop growth variables and yield?
2) Does elevation enhance or lower the magnitude of key crop variables such as the length of the growing season (LGS), carbon allocation to different parts of the plant, leaf area index and yield, and their interactions?

Our strategy is first to analyse the inter-annual SW↓, precipitation and temperature patterns during 2001–2010. We identify climatologically normal, dry and wet *belg* seasons using anomaly calculations and the Standardized Precipitation Index (SPI) (Raja et al., 2014). This enables us to analyse the sensitivity of key crop metrics (LGS, LAI, the carbon stored in the various crop organs, and the crop yield) to weather variations, soil characteristics, and crop management options. Finally, we evaluate the performance of our weather model with currently available meteorological observations at low-elevation and high-elevation stations, and compare our results with the available literature for the crop model (IPC, 2009; Mazengia et al., 2015; Tufa, 2013). To the best of our knowledge, this is the first study of the influence of weather on a crop in a tropical highland region with such a long integration time and fine spatial resolution.

2. Methods

2.1. Weather model

The numerical atmospheric model experiment employed the WRF model, version 3.4.1 (Skamarock et al., 2005). The model is configured in domains with different horizontal grid resolutions: one coarse resolution domain and three consecutively nested domains with increasingly finer resolutions. In this study, we only use the outer domain with the coarse resolution and the inner domain with the finer resolution. A summary of the numerical settings and physical parameterisation schemes applied is provided in Table S2 (see a supplementary material attached to this article). The model initialisation was as follows: independent 48 h (data recorded every hour) WRF runs were performed for the period 2001–2010. The model's initial and lateral boundary conditions were prescribed from the ECMWF ERA-interim reanalysis data (Dee et al., 2011). The first 24 h was discarded as a model spin-up for the physical processes that were parameterised. The meteorological output for the second day (interval 24–48 h) was considered for that day. This modelling strategy was suggested by Jiménez et al. (2010, 2011) as a way to obtain an appropriate balance between an accurate representation of the complex orography and land-use characteristics (local/regional conditions) without departing from the synoptic dynamical features (Jiménez et al., 2016). By combining high resolution (2 km × 2 km) with long model runs (10-year), we attempt to represent the spatial variability and obtain robust statistics.

2.2. The crop model

The GECROS crop systems dynamic model requires six weather variables, namely SW↓, precipitation, maximum temperature (T_{max}), minimum temperature (T_{min}), vapour pressure deficit (VPD) and wind speed, all on a daily basis. The model runs with a time step of one day with a diurnal variation estimates in the environmental inputs (YL05). These variables are indicated in Table S3 and are calculated by the WRF model. The GECROS model was designed to study the responses of biomass and dry matter production in arable crops to both environmental and genotypic characteristics (Khan, 2012; Yin and van Laar, 2005). The model has been tested and widely used to simulate crop growth (Combe et al., 2015; Gu et al., 2014; Yin and Struik, 2010) and potato in particular (Khan et al., 2014). Since the representation of evaporation is crucial here, we follow the improvements suggested by Combe et al. (2015) to obtain more reliable surface energy budget estimates. Table S3 shows parameter/variable values considered from the literature other than those mentioned in YL05. Detailed GECROS model settings for the control run are presented in Table S4 to Table S13, where the control run represents the GECROS model run with the best available model setting.

2.3. Weather observations

Since 1974, weather conditions have been recorded in Arba Minch in the lowlands (1,200 m a.s.l.) (Ayana, 2011). The Arba Minch weather station was re-located and re-established in 1987 by the Ethiopian National Meteorological Services Agency (NMSA). It is a WMO 1st class synoptic weather station located at 6.05 °N and 37.55 °E. Weather variables such as temperatures, relative humidity, precipitation, winds, hours of sunshine, atmospheric pressure, clouds, visibility, evapotranspiration, *etc.* are recorded/observed on a three-hourly/daily basis (during daytime hours) manually (NMSA, 2018).

We also used weather observations collected in Chencha, in the Gamo Highlands (2,632 m a.s.l.). This station is a WMO 4th class station category, from which we used the precipitation data only (NMSA, 2018). We collected additional data from our recently (2013) established automatic weather station in Chencha. A more detailed description of the observation data used in this article is provided in Table S12.

2.4. Soil data

The GECROS crop model is coupled with a process based soil model (YL05). In agreement with the high topographic resolution prescribed to obtain reliable spatiotemporal meteorological variables, we used high-resolution soil information. Soil parameters such percentage of clay in the soil, soil water content at maximum holding capacity, soil water content at field capacity, minimum soil water content and total organic carbon in the soil (TOC) are required as model input. These parameters were calculated from the International Soil Reference and Information Centre (ISRIC), world soil information, Africa Soil Information Service (AfSIS) project database (Leenaars et al., 2014). 1 km × 1 km resolution data in the top 60 cm were aggregated and interpolated to fit the fine resolution domain.

2.5. Validation of the meteorological model

WRF meteorological results were validated against observations collected at the two stations described in section 2.3. Our validation of weather will focus on the variables SW↓, precipitation, T_{max} and T_{min}. We selected these weather variables because they are the key atmospheric variables that have the strongest influence on crop growth. The SW↓ affects the light-use efficiency of crops. Precipitation is highly correlated with SW↓ by clouds. The amount, frequency, and location of precipitation are key factors; since crop stress and yield depend on soil moisture. Temperature strongly influences physiological and biophysical characteristics such as net photosynthesis, canopy development, dry matter accumulation, and partitioning, and absolute tuber growth rate of potatoes (Ewing, 1981; Hammes and De Jager, 1990; Khan, 2012; van Dam et al., 1996).

Since our aim was to determine how domain resolution affects the representation of elevation and the resulting weather simulations, we compare the observed weather variables with the modelled weather variables from both the coarse and fine resolution domains. We compare the 10-year mean modelled weather variables of the 840 grid cells in the fine resolution domain together with the four overlapping grid cells in the coarse resolution domain. We also show the elevational gradients of SW↓, precipitation, T_{max} and T_{min}. Finally, we express the performance of the WRF model using statistical metrics such as the Root-Mean-Square Error (RMSE), the Mean Bias Error (MBE) and the coefficient of determination (r^2) (Willmott, 1982).

2.6. Strategy for the crop model sensitivity study

To compensate for the lack of potato yield data during the 10-years period, we investigated how simulated crop growth in GECROS model responds to weather (SW↓, T_{max}, T_{min}, VPD, precipitation, and [CO_2]), edaphic variables (soil type, soil moisture content and TOC), crop parameters, and crop management options.

The model sensitivity experimental strategy was as follows. We varied the meteorological and other variables over a range representing the uncertainties of the weather model inspired by the model uncertainties discussed in the previous section. The selected range covers the change in meteorological variables under future climate scenarios, and is aimed at understanding how the crop dynamics processes respond to the change in climate. The IPCC climate projections for eastern Africa show increased precipitation (up to ~ 18%) in the warming climate (Stocker et al., 2013; van Oldenborgh et al., 2013). Our edaphic model sensitivity experiments are indicative of how the attainable crop yield, LGS and LAI respond to variations in soil fertility, soil type, and moisture content. Attainable yield is defined here are 80% of the potential yield, which in turn defined as *'the theoretical yield that can be calculated or modelled for a certain cultivar grown in a certain environment without any limiting or reducing factor being present'* (Haverkort and Struik, 2015). Similarly, the crop parameter model experiments tell us how the crop yield variables differ with potato variety.

We based the sensitivity experiment on the weather during the 2006 *belg* season, which is representative of a climatologically normal year, in the potato-growing zone in our region. The SW↓ was varied within the range of $19.5 \pm 4.2\,\mathrm{MJ.m^{-2}.d^{-1}}$, with a ± 1% simulation resolution interval from the mean. We varied the temperature around the average of 17 °C within a range of 15 °C to 19 °C, with 0.5 °C model run range, as suggested in van Oldenborgh et al. (2013). This analysis was conducted with the assumption that the relative humidity remains constant (Stocker et al., 2013), as the absolute humidity rises with rising temperature (Rieck et al., 2012). We varied precipitation in the range of $10.6 \pm 2.2\,\mathrm{mm.d^{-1}}$ with ± 5% model run resolution. We took a similar approach for the other atmospheric variables. For the soil, crop variables/parameters, and crop management options, we employed a realistic range around the selected inputs. For each value in the ranges thus created, the GECROS model was run separately in order to study the sensitivity of crop growth to the individual input variable.

3. Model evaluation and parameter sensitivity analysis

This section presents the results of the weather model evaluation as described in section 2.5 and the crop model sensitivity analysis as described in section 2.6.

3.1. Weather model evaluation

Fig. 1 shows the results of the weather model validation. The SW↓ decreased with elevation that was related to an increase in cloudiness at higher altitudes. At the same elevation, SW↓ displayed different patterns in the coarse and fine resolution domains: for the coarse resolution domain, it was underestimated and for the fine resolution domain, it was overestimated. The order of magnitude of these deviations with respect to the observations was similar: ~ $60\,\mathrm{W.m^{-2}}$ less in the coarse resolution domain and $50\,\mathrm{W.m^{-2}}$ more in the fine resolution domain at the lowland station. At the highland station, the bias became slightly less, but it was still significant. We attribute these differences to the representation of convection in WRF in the coarse and fine resolution domains. Note that for the coarse resolution domain, convection was approximated or parameterised whereas at the domain with finer resolution it was explicitly calculated (Table S2). It is important to stress that the different results due to the differences in the calculations of convection affect not only the SW↓ but also the precipitation, T_{max} and T_{min} results. These findings emphasise the critical role played by clouds and aerosols in the calculation of the SW↓, a key variable in the crop dynamics model.

Precipitation increased exponentially with altitude (Fig. 1). There was a satisfactory agreement with the modelled precipitation in the coarse resolution domain at both lowland (almost no bias) and highland (bias $\sim +1.0\,\mathrm{mm.d^{-1}}$) locations. However, we found both a dry ($\sim 1.5\,\mathrm{mm.d^{-1}}$) and a large wet ($\sim 3.5\,\mathrm{mm.d^{-1}}$) bias in both Arba Minch and Chencha in the fine resolution domain. This large rainfall bias occurred in spite of a better description of the elevation and presumably better model physics in the finer resolution domain. The reason for this large bias is uncertain, and our evaluation will need to be continued in the near future, particularly by using better measurements

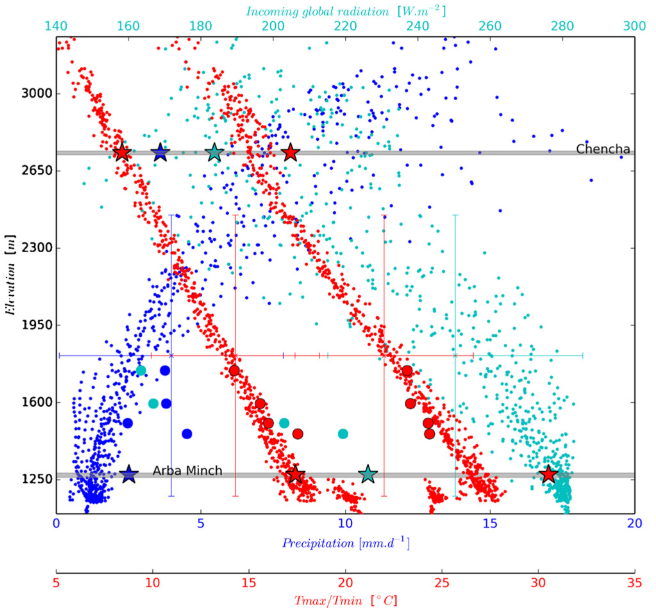

Fig. 1. The relationships between incoming global radiation [W m^{-2}] (cyan dots), precipitation [mm d^{-1}] (blue dots) and T_{max} and T_{min} [°C] (red dots) and with elevation [m]. The small dots represent 840 individual grid cells in the fine resolution domain. The filled circles represent the four individual grid cells in the coarse resolution domain that overlap with the fine resolution domain. The WRF analysis covers the averages of the daily means during 10-years. The observational data covers climatological period. The stars designate observed climatology for Arba Minch and Chencha (corrected for elevation of the stations). The error bars indicate variability in the fine resolution domain. The crosshairs show the mean values of the given weather variables/elevation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of rainfall make use of a dense network of stations across elevation gradients (section 5).

We found that T_{max} and T_{min} declined linearly with elevation (Fig. 1). At Arba Minch T_{max} was negatively biased by ~ -7 and -3 °C in the coarse and fine resolution domains, respectively. At Chencha T_{max} was positively biased in the coarse resolution domain and negatively biased in the fine resolutions (by ~ + 8 °C and ~ −1 °C respectively). T_{min} was well represented at Arba Minch in both resolution domains. It was in good agreement in the fine resolution domain and largely positively biased (~ + 7 °C) in the coarse resolution domain at Chencha. We conducted a statistical analysis to test the performance of the weather model at both locations.

Table 1 shows how the WRF model performed compared to the observed weather for Arba Minch and Chencha using daily averages. We validated the WRF model at the grid points at which the Arba Minch and Chencha stations are located. Our approach was to use the data with a daily temporal scale since here we were interested in studying the impact of fine spatiotemporal scales on meteorology and crop dynamics during the 10-year period. For Chencha, only precipitation observations were available for between 2001 and 2010. The model elevation of the Arba Minch and Chencha sites were modelled to be 62 and 100 m respectively above their actual elevation in the fine resolution domain. In the coarse resolution domain, Arba Minch and Chencha were modelled at 360 and 1,050 m respectively above and below their actual elevations. We corrected the modelled temperature for elevation bias using the international standard atmosphere (-0.65 °C/100 m) (Kunz et al., 2007).

The first finding was that there was no general improvement in the domain with finer elevation and resolution for the variables under study. Our results showed that the model was negatively biased in terms of T_{max} (12.7 and 3.2 °C) for both coarse and fine resolution domains. Possible explanations for the underestimates are: (i) the initial and boundary conditions provided by the ECMWF ERA-interim reanalysis data may give a cold temperature bias for the tropical and mountainous region (Jury, 2014a) and (ii) WRF has a cold temperature bias (Steeneveld et al., 2008). Similarly, T_{min} was underestimated

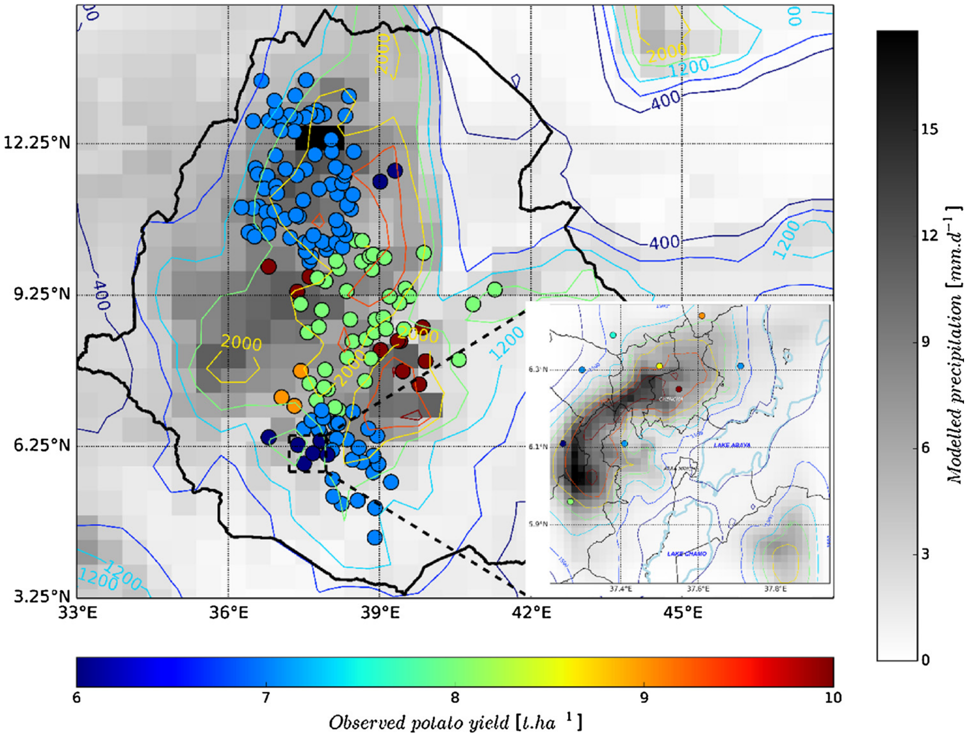

Fig. 2. 10-year mean of WRF modelled precipitation [mm d^{-1}] – shaded region, topography – contour lines [m] and the observed potato yield – scattered dots in [t ha^{-1}]. The larger plot shows Ethiopia (part of the coarse resolution domain) with spatial resolution of 54 km × 54 km. The dashed square in the figure represents the fine resolution domain, which is magnified and indicated in the right corner. The resolution of the finer resolution domain is 2 km × 2 km and covers 84 km × 84 km area, located in the Gamo Highlands. Each dot represents potato yield per 1,000 ha in the coarser resolution domain. The colour bar scales are applicable to both domains. The potato yield and production observation data are taken from the (IPC, 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Statistical WRF model validation using daily weather station observations for Arba Minch and Chencha for the coarse and fine resolution domains. The analysis was carried out on daily data.

			WRF mean		MBE		RMSE		*r2*	
Station	**Weather variable**	**Observed mean**	**coarse**	**fine**	**coarse**	**fine**	**coarse**	**fine**	**coarse**	**fine**
Arba Minch	T_{max} [°C]	30.5	17.8	27.3	−12.7	−3.2	12.9	3.9	0.26	0.26
	T_{min} [°C]	17.4	9.5	17.9	−7.7	0.5	8.0	1.9	0.12	0.19
	Precipitation [mm.d^{-1}]	2.5	2.5	1.2	−0.1	−1.3	7.2	7.7	0.05	0.01
Chencha	T_{max} [°C]		17.9	16.8						
	T_{min} [°C]		11.0	9.1						
	Precipitation [mm.d^{-1}]	3.5	4.5	7.2	1.0	3.7	8.8	13.0	0.05	0.05

(7.7 °C) in the coarse resolution domain, despite the fact that T_{min} was well represented in the fine resolution domain with values for MBE and RMSE of 0.5 and 1.9 °C, respectively. Comparing the two model resolutions, the fine resolution domain was closer to the measurements. This was primarily attributable to the direct relationship between temperature and elevation, and a better representation of topography in the fine compared to the coarse resolution domain (section 4.1).

Precipitation was underestimated in the lowlands (*i.e.,* in Arba Minch) by 0.1 and 1.3 mm.d^{-1} in the coarse and fine resolution domains, respectively. However, in the highlands (*i.e.*, in Chencha), our comparison deteriorated, with a tendency towards more rain in the model (+1.0 and +3.7 mm.d^{-1} for the fine and coarse resolution domains, respectively) compared to the observations. We hypothesise that the better representation of topography in the fine resolution domain could trigger more convection than in the coarse resolution domain. There may also be uncertainty in the precipitation measurements because the rain gauges are manually operated and the treatment of the missing data by the National Meteorological Agency – Ethiopia (NMA) could also lead to bias.

A number of authors have shown that the precipitation modelled using the ECMWF ERA-interim reanalysis data has a large wet bias over the Ethiopian Highlands and dry bias over the lowlands (Diro et al., 2011; Dutra et al., 2013; Jury, 2014a; Tsidu, 2012), which agrees with our finding. For example, Diro et al. (2011) has indicated that the ECMWF ERA-interim (1989–2001) reanalysis data underestimated the south and south-eastern lowland regions precipitation by nearly 30 mm.month^{-1} during the *belg* season, as compared to the gauged stations. This result is consistent with our findings at the Arba Minch station. Also, note the opposite behaviour between SW↓ and precipitation, as the first exponentially increases while the latter decreases with elevation (Fig. 1).

It is also interesting to discuss our validation using different averaging periods, in particular monthly and yearly ones for precipitation. The monthly averages indicate a significant fit and comparable performance between the coarse and fine resolution domains (r^2 is respectively 0.68 and 0.66 for the coarse and fine resolution domains in Arba Minch, and 0.61 and 0.60 for the coarse and fine resolution domains in Chencha). Although the annual precipitation modelled, in Arba Minch, by the finer resolution domain has a better fit (r^2 = 0.94) than with the coarse resolution domain (r^2 = 0.89), the opposite is true for the daily precipitation, as the one modelled in the coarse resolution domain results in an r^2 = 0.05, compare to r^2 = 0.01 in the fine resolution domain. We can attribute these opposite outcomes to (a) the smoothing of the complex terrain (which modifies the modelled precipitation rates); (b) the actual displacement of the site elevation in the model (inherent to the assumed model resolution) and (c) the WRF model physics representation (Kerandi et al., 2018; Riddle and Cook, 2008). For instance, the Arba Minch station is represented by WRF to be at 1,574 m a.s.l. in the coarse resolution domain and 1,274 m a.s.l. in the fine resolution domain, but is located at 1,212 m a.s.l.

3.2. Sensitivity of crop variables to the weather variability

In the absence of time series of crop yield observations during 2001–2010 to validate our results, we first show the strong relation between meteorology and potato yield observed in 2000, and the role played by elevation. In Fig. 2, we combined the observed potato yield [t. ha^{-1}] and the area of production for Ethiopia during the year 2000, as illustrated by the International Potato Centre (IPC, 2009) and related to the precipitation modelled with WRF. The inset shows the precipitation results obtained by WRF using the finer resolution domain. Each dot in the plot in the larger plot represents potato yield [t. ha^{-1}]. The background shaded region (with topographical contours) shows 10-year-average modelled precipitation [mm.d^{-1}]. The figure indicates that the most productive potato growing regions in Ethiopia are the mid-elevations (from 2,000–2,400 m a.s.l., which have moderate annual precipitation: ~ 6–9 mm.d^{-1} and produce annual yields > 10 t.ha^{-1}), the Rift-Valley system, and the northern and eastern escarpments along the valley. The region represented by the broken line indicates the fine resolution domain, which is also indicated by the overlaid map at the right lower side of the figure. Note that the region (the Gamo Highlands) has one of the lowest potato yields in the country (< 7 t.ha^{-1}) (Dersseh et al., 2016; Mazengia et al., 2015). However, due to its suitable weather and agro-ecology, it has large production potential in the future.

Based on the strategy designed for the crop model sensitivity experiment in section 2.6, the variations introduced in weather and summary of the main results are presented in detail in Table 2.

Fig. 3 shows how the attainable yield (black – left axis) and LGS (blue – right axis) responded to variations in atmospheric variables and crop management options. The relationship between the meteorology and the crop variables was as follows: variations in the SW↓ controlled by clouds affected the major meteorological crop drivers and these in turn all affected crop growth (a); precipitation, which affected soil moisture and impacted the crop water requirement (b); and T_{max} and T_{min} were associated with extreme meteorological conditions such as heat waves or cold night events and influence crop growth (c and d).

Fig. 3a shows an almost linear decline in yield (23.5 to 20.0 t.ha^{-1}) as SW↓ increases from 15.0 to 23.5 MJ.m^{-2}.d^{-1}. This finding is counterintuitive, but our explanation is as follows: by increasing the SW↓, T_{max} and T_{min}, LGS and LAI are also varying and diminishing, as shown in Fig. 3. These lead to the crop having a shorter growing season during which to accumulate additional carbon with the decreased light interception (which limits the amount of photosynthesis performed by the plant) due to the reduced LAI. The LGS and LAI can be considered as an integral metric that embeds the meteorological dependencies and have a direct impact on the crop yield.

Our sensitivity analysis also indicated that the attainable yield declined non-linearly by ~17% when precipitation increased from 8.0 to 12.5 mm.d^{-1}, whereas the LGS remained constant (Fig. 3b). This counterintuitive result may be explained as follows: the soil model in

Table 2

Design of the model sensitivity analysis for crop outputs on atmospheric, edaphic and crop variables and crop management options. The table shows the range of the model sensitivity experiment, the difference between the highest and lowest LGS [day] amongst experiments, the difference between the average LGS of experiments of a variable/parameter and the LGS of the control run, and related literature/assumptions.

Experiment category	Variable/parameter	Unit	Range	ΔLGS[a] [d]	ΔLGS[b] [d]	References/ Assumptions
Atmospheric variables	SW↓	$MJ.\ m^{-2}.d^{-1}$	15 – 23.5	28	4	(Haverkort, 1990; Haverkort and Harris, 1986, 1987)
	T_{max}	°C	15 – 21	63	2	(van Oldenborgh et al., 2013)
	T_{min}	°C	7 – 13	66	−2	(van Oldenborgh et al., 2013)
	VPD	kPa	0.05 – 0.38	10	1	(Kiniry et al., 1998)
	Precipitation	$mm.d^{-1}$	8 – 12.25	0	0	(Stocker et al., 2013)
	[CO_2]	ppm	350 – 750	8	3	(Meinshausen et al., 2011)
Edaphic variables	Total Organic Carbon (TOC)	$kg\ C.\ m^{-2}$	0 – 20	1	0	Model experiment
	Soil microbial & humified organic matter	$kg\ C.\ m^{-2}$	0 – 10	3	1	Model experiment
	Percent clay	%	0 – 50	0	0	Model experiment
	Soil water content at maximum holding capacity	$m^3.\ m^{-3}$	0 – 1	22	−8	Model experiment
	Soil water content at field capacity	$m^3.\ m^{-3}$	0 – 1	4	0	Model experiment
	Minimum soil water content	$m^3.\ m^{-3}$	0 – 1	22	−9	Model experiment
Crop parameters	Efficiency of germination	$g.\ g^{-1}$	0.1 – 0.95	12	4	(YL05)
	Seed weight	$g.seed^{-1}$	20 – 30	4	1	(YL05)
	Maximum crop nitrogen uptake	$g\ N.\ m^{-2}.d^{-1}$	0.34 – 0.46	0	0	(YL05)
	Maximum plant height	m	0.6 – 1.5	5	1	(YL05)
	Stem dry weight per unit of plant height	$g.\ m^{-2}.\ m^{-1}$	145 – 195	2	0	(YL05)
Crop management options	Fertilizer dose applied	$g.\ m^{-2}.season^{-1}$	0 – 40	12	0	Model experiment
	Planting date variations	d	Jan 1 – Aug 1	57	18	(Wang et al., 2015)

[a] The difference between the shortest and longest LGS [day] amongst the sensitivity experiments for the variable.

[b] The deviation of the averages LGS in the sensitivity experiments from the 2006 *belg* control run LGS (i.e. 120 days).

GECROS is mainly driven by the amount of precipitation and fertilization. Increasing precipitation in the sensitivity study enhances the soil moisture content, which facilitates drainage and leaching of nutrients such as nitrate-nitrogen to the ground water reservoir (YL05). The reduction in nitrate-nitrogen reduces its availability to the plants, as discussed in Waddell et al. (2000). Note that climate models project increased precipitation (up to ~ 18%) for Eastern Africa by the end of this century (Stocker et al., 2013), which is likely to reduce future potato productivity.

Fig. 3c and d show that increases in T_{max} and T_{min} reduced yield by 7 and 13%, respectively, which agrees with the findings of Resop et al. (2014). Haverkort and Struik (2015) suggested that the potential global yield of potato would fall by 18–32% as a consequence of a global temperature rise of + 2.5 °C in 2069. The temperature increase in the future climate significantly shortens the LGS, as discussed in van De Geijn and Dijkstra (1995), emphasising the need for climate change adaptations for such global change (Haverkort and Struik, 2015). Although yield increases at lower temperatures, crop development is slower. This can increase the risk of damaging night frosts in the highlands, as discussed in Haverkort and Verhagen (2008). Forecasting this phenomenon requires the use of detailed elevation maps and high model resolution, as is presented here. Additional model sensitivity experiment results and discussion are included in Figs. S1–S3.

Most model sensitivity experiments showed variations in the LGS (within runs of a variable and/or as relative to the control run) (Fig. 3). This was because the variable under study influenced the crop growth

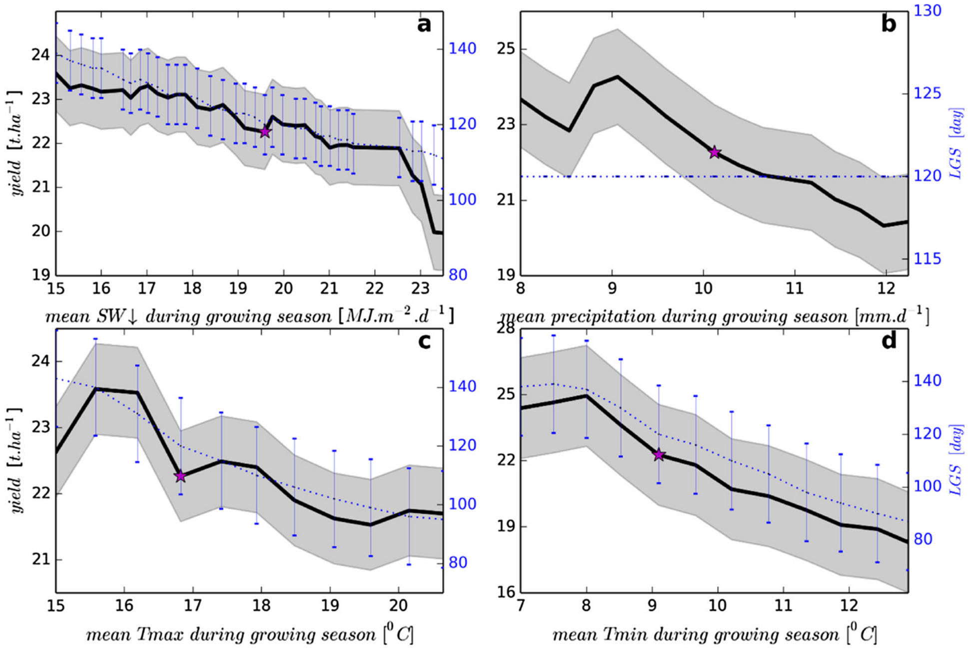

Fig. 3. GECROS model sensitivity analysis for attainable potato fresh tuber yield [$t\,ha^{-1}$] (left-axis – solid-line) and LGS [d] (right-axis – dot line). Variations in the means in atmospheric variables: SW↓ [$MJ\,m^{-2}.d^{-1}$] (a), precipitation [$mm.d^{-1}$] (b), and T_{max} and T_{min} [°C] (c and d) with the corresponding LGS [d] (left-axis) for Chencha during the 2006 *belg* season. In all the figures, the LGS variation is included. The shaded/line error bars show the standard deviations of yield/LGS. The stars denote yield for the control run. The scales between panels on the left and those on the right are different.

Table 3
The relative sensitivities of atmospheric, edaphic, crop variables and crop management options. The GECROS model values are numerically normalized and calculated using the equation (3.1). The variables/parameters are ordered from high sensitivity to low.

Categories	Yield improving	S_R [%]	Yield-reducing	S_R [%]
Atmospheric variables	[CO_2]	31.9	Precipitation	−37.9
	VPD	2.1	T_{min}	−37.7
			SW↓	−35.9
			T_{max}	−24.1
Edaphic variables	BHC	70.3	TOC	−74.4
			Percent clay	−47.1
	Soil water content at field capacity	14.2	Soil water content at minimum holding capacity	−12.4
			Soil water content at maximum holding capacity	−1.2
Crop parameters	Seed weight	60.5	Plant height	−3.6
	Efficiency of germination	37.0	Stem dry weight per unit of plant height	−0.3
Crop management options	Fertilizer dose	51.7		
	Planting date	9.2		

rate, and in consequence the LGS and the weather to which the crop was exposed during its growth. However, overall the imposed variation dominated over the secondary variations in weather conditions during the growing season. In general, an increase in LGS tended to enhance yield. However, the larger LGS probably increased exposure to biological risks such as pests and diseases, even though these were not accounted for in the model (Haverkort and Struik, 2015; Haverkort et al., 2012; Tufa, 2013) and meteorological stresses (*e.g.*, droughts, heat waves, frosts) (Haverkort and Struik, 2015; Haverkort and Verhagen, 2008).

To conclude the model evaluation and parameter sensitivity section, a further quantification was performed to determine the most sensitive variable/parameters to crop yield. To do so, we calculated the relative sensitivities of the variable/parameter by normalizing the experiments, using equation (3.1).

$$S_R = \partial(Y_{expt}/Y_{cont})/\partial(P_{expt}/P_{cont}) \tag{3.1}$$

Where Y_{expt} represents the yield in the sensitivity experiment, Y_{cont} yield in the control run, P_{expt} the parameter value in the sensitivity experiment and P_{cont} the parameter value in the control run, respectively.

Table 3 shows the normalised values [%], which are categorised as increasing or decreasing the yields realised by variables/parameters in the four (atmospheric, edaphic, crop parameter and management) categories. The highest increases and decreases in yield in response to atmospheric variables corresponded to [CO_2] and precipitation, respectively. In the crop parameters category, seed weight and plant height were the most important yield parameters, respectively. Crop management options such as fertiliser dose and differences in planting dates correlated positively with attainable yield. Of the four categories, the edaphic variables such as Biomass Humified Soil (BHC) and TOC were the most important yield-increasing and -decreasing variables, respectively.

4. Results

4.1. Representation of topographical variability: the need for high-resolution modelling

The topography of the region under study was highly variable: in a radius of ~ 50 km, there were differences of up to 2,500 m in elevation.

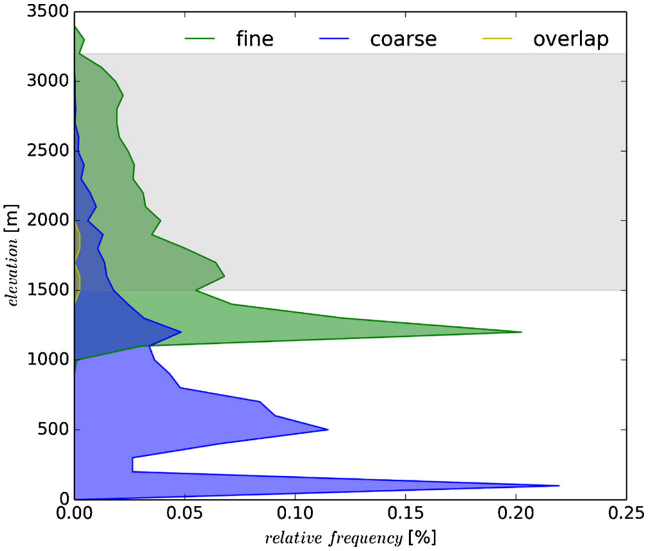

Fig. 4. The distribution of topography in the coarse and fine resolution domains. The grey shaded area marks the elevation zone where potato can be grown in the current climate (Tufa, 2013). In the coarse resolution domain, 8% of the grid points are within the potato growing area, in the fine resolution domain 51%, showing that the coarse resolution domain has more grid points with low elevation and the finer resolution domain has more locations with intermediate elevations. The green, blue shaded areas show the frequency distributions of the elevations in the coarse and fine resolution domain. The coarse resolution domain covers a larger area than the fine resolution domain. The yellow shaded region indicates the elevation range of the four grid points in the coarse resolution domain that includes the same area of the fine resolution domain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Meteorological conditions changed with elevation at the Gamo Highlands, influenced by a combination of synoptic and local circulations that led to high variability in the patterns of temperature, clouds, and precipitation (Fig. 1).

Our first analysis focused on how topography influenced the meteorological crop drivers. In particular, SW↓, precipitation, T_{max} and T_{min} influenced the various crop variables related to potato growth and yield. To this end, we show first in Fig. 4 the relative topographic variations: the ‘green’, ‘blue’ and ‘yellow’ shaded regions indicate variations in elevation of the entire coarse and fine resolution domains that are prescribed in the WRF numerical experiments and the grid points that the coarse and fine resolution domains share.

The topography imposed at the coarser resolution domain showed an elevation that ranges from 0 to 3,000 m a.s.l. (marked by the blue area in Fig. 4). It is relevant to our study that the East-African Highlands including the Gamo Highlands (west of Abaya and Chamo Lakes, roughly 100 km long and 30 km wide) (Freeman, 2002) are highly smoothed and hence the mountain peaks in the coarse resolution domain were shown hundreds of meters lower than in reality. Two representative examples in our study used in the model validation are the weather stations in Arba Minch, which were located 400 m higher than in reality, *i.e.*, 1,200 m a.s.l. and that of Chencha 1,100 m lower than in reality, *i.e.,* 2,632 m a.s.l. The figure also indicates that only 8% of the grid cells were in the potato-growing range as defined by Tufa (2013). In the fine resolution domain, the elevation range from Lake Chamo, the lowest point in the domain (~ 1,000 m a.s.l.) to the top of Guge Mountain, the highest point in the domain (~ 3,500 m a.s.l.) was well represented (see green area in Fig. 4). Note that there are only four grid points in the coarse resolution domain that are within the bounds of the fine resolution domain (see yellow area in Fig. 4). This analysis shows that the topography resolution modelled by the coarse resolution domain smoothed the topography and therefore could affect the potato-growing region of the Gamo Highlands.

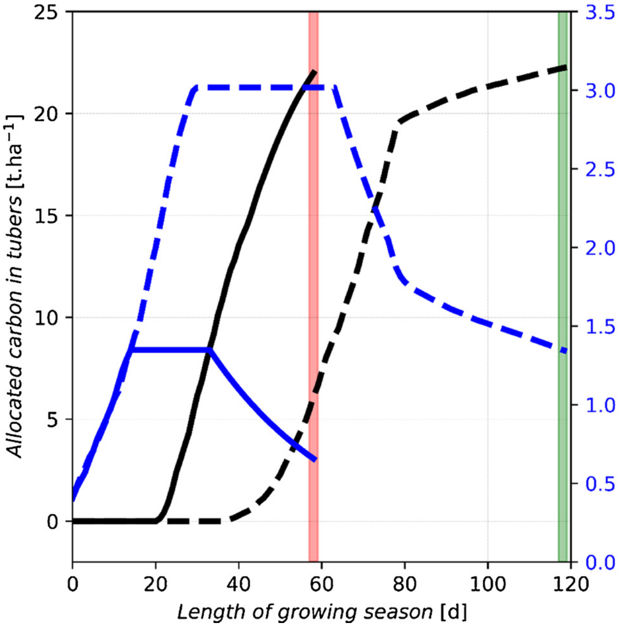

Fig. 5. GECROS modelled allocated carbon in tubers [t ha^{-1}] (left-axis, black lines) and LAI [-] (right-axis, blue lines) as a function of the LGS during the 2006 *belg* harvest season. The solid lines show model output using the coarse resolution domain's weather input and dotted lines represent output using the fine resolution domain's weather input. The red and green lines show the harvest days of the coarse and fine resolution domains, respectively. The analysis covers the entire length of the growing season [d] at the grid point that represent Chencha station in both model domains. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We therefore expect that smoothing of the elevation will affect the WRF simulation of meteorological variables. More specifically, when we analysed the results for the coarse resolution domain, which could be considered as a representative domain resolution as used in current weather-crop models and compared them with those by the high-resolution domain, we found a better agreement for T_{max} and T_{min} compared to the observations. This was quantified in terms of MBE, RMSE, and r^2 between modelled and observed weather variables, as shown in Fig. 1 and Table 1. Furthermore, on a seasonal scale, which is important for crop growth, we found a strong correlation ($r^2 > 0.89$) between modelled and gauged stations and better statistics for the fine resolution than the coarse resolution domain.

4.2. Relating the resolution of elevation to crop yield

In order to determine the sensitivity of the influence of the prescribed topography on meteorological crop drivers and thus on simulated crop growth, we focused on the following matrices: the LGS and LAI. These crop variables connect the meteorological variables to the potato crop dynamics, mainly the allocated carbon in tubers, or the attainable yield.

Fig. 5 shows GECROS simulated allocated carbon in tubers and LAI as a function of the LGS during 2006 at Chencha, where the weather station is situated. In order to present the results in a systematic manner, we first studied the meteorological and crop variables in *belg* 2006 and then analysed the variability of these variables in the *belg* seasons through the 10-year period of the study. We identified the *belg* season of 2006 as a normal climatological year based on the average precipitation of 9.7 mm.d^{-1} as opposed to the driest year of 2008 (6.1 mm.d^{-1}) and the wettest year, 2010 (14.6 mm.d^{-1}). The year's *belg* season was also climatologically normal in terms of mean temperature (27.7 °C) as compared to the coolest, 2008 (27.0 °C) and the warmest, 2010 (28.3 °C).

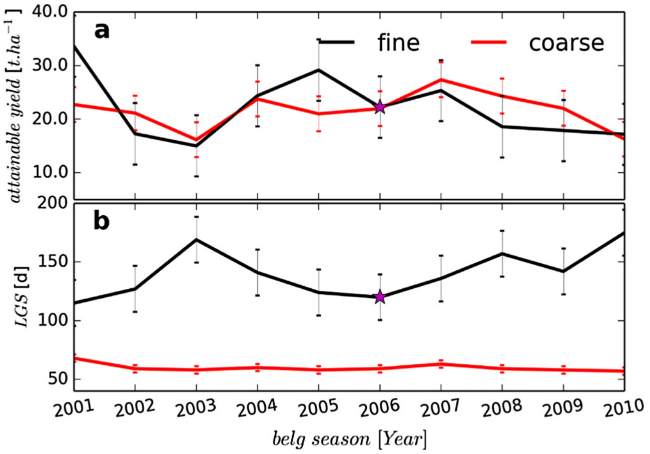

Fig. 6. Inter-annual variability in attainable fresh-matter yield [t ha^{-1}] (a) and LGS (b) modelled by GECROS using the meteorological input from the coarse and fine resolution domain at the grid point that represents Chencha station for *belg* season in 2001 - 2010. The stars denote the control run (*i.e.* yield or LGS during the 2006 *belg* season). The error bars indicate the mean ± standard deviations of the 10-year yields. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The calculated LGS was 59 days in the coarse resolution domain, shorter than the more realistic LGS of 90–150 days (FAO, 2008). The maximum LAI was also underestimated at the given value of 1.35, much lower than the optimal maximum LAI of a potato crop: 3.0–5.4 (Harper, 1963). In contrast, using the data calculated with the finer resolution domain, the LGS and the LAI were 120 days and 3.02, respectively (Fig. 5). As mentioned above, in the coarse resolution model the elevation of Chencha was ~1,100 m below the actual elevation. As a result, the averaged *belg* season was 8.5 °C warmer and 4.3 mm.d^{-1} drier than in the fine resolution domain. This caused the crop to mature too early, with a low maximum value for the LAI. Despite significant differences in modelled weather and crop growth calculated in the coarse and fine resolution domains, Fig. 5 shows that the yields were very similar in both domains during the 2006 *belg* season. This finding is discussed in detail and in context, below and in section 5.

Fig. 6 shows how GECROS modelled attainable potato yield (a) and LGS (b) for the Chencha station for the 10-year period during the *belg* growing seasons using the modelled coarse and fine resolution domains weather inputs. To complete the figure, we add an observed reference potato yield for 2001–2010 in the southern Ethiopia to be < 8 t.ha^{-1} as indicated in Fig. 2 and by (Hirpa et al., 2010; Mazengia et al., 2015). Other experts have estimated the potential fresh tuber yield in Chencha district in the *belg* season to be about 30 t.ha^{-1}, although the actual yield is much lower (*i.e.,* ~8 t.ha^{-1}) (Haverkort et al., 2012).

The pattern in inter-annual variability in potato yield was very similar in both domains (Fig. 5a). The average attainable yields calculated were in the range of 21.7 ± 3.2 and 22.1 ± 5.7 t.ha^{-1} using the weather modelled in the coarse and fine resolution domains, respectively. The yields were comparable with the modelled yield during the 2006 *belg* season (Fig. 5). Moreover, the yield modelled for the fine resolution domain was almost constant over the range of elevations in the Gamo Highlands (Fig. 7). However, and as in 2006, the simulated LGS for both domains was very different. We calculated 60 ± 3 and 141 ± 20 LGS [d] for the coarse and fine resolution domains, respectively (Fig. 5b)[b]. It is therefore of interest to further study how the LGS and the potato yield change as a function of elevation.

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[b] Additional differences in the outputs of the coarse and fine resolutions are presented in Table S13.

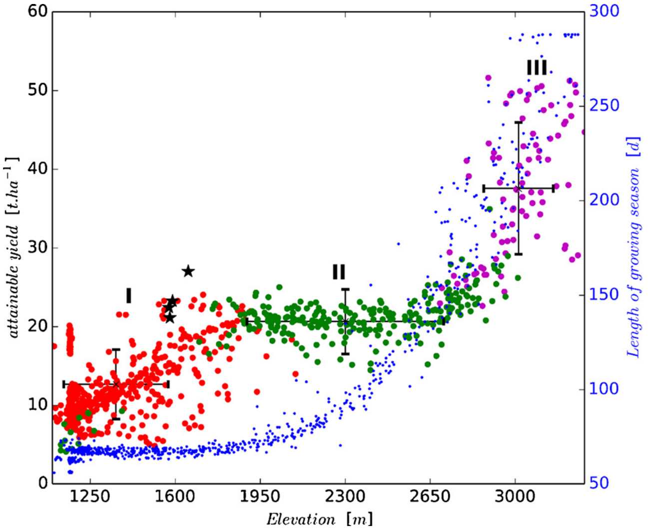

Fig. 7. Relationship between attainable yield (left-axis) and elevation, showing that the yield is fairly constant in the altitude range where potato mostly grows in the Gamo Highlands. The scattered dots indicate fine resolution domain grid cells that spatially overlap with the coarse resolution domain (black star) averaged during the 10 years of *belg* harvests. The error bars (mean ± standard deviations) are calculated for grid points with LGS < 70 (red dots – region-I), between 70–195 (green dots – region-II), and > 195 (pink dots – region-III) days, respectively. The blue dots with the corresponding y-axis (right side) indicate the LGS. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 7 shows the potato yield and length of growing season for (i) four grid cells in the coarse resolution domain (black stars) that share their spatial location with the fine resolution domain; (ii) 840 grid cells in the fine resolution domain (all dots). As the most representative variable, we show the attainable yield (red, green, and purple dots and left y-axis) and the LGS (fine blue dots and right y-axis). The coarse resolution domain led to a yield of 23.4 ± 2.9 t.ha^{-1}. For the fine resolution domain, we found that potato grew in the optimal elevation range (1,600 m – 2,700 m a.s.l.) with an attainable yield range of 20.7 ± 4.1 t.ha^{-1}. This optimal region was further corroborated by the calculated values of LGS between 70–195 days that once again were in the range of the expected values for the potato growing cycle. GECROS also calculates yield for LGS outside this range, but its estimates are not realistic in terms of potato growth characteristics (FAO, 2008; Harper, 1963). For LGS < 70 days, the calculated yield was 12.7 ± 4.4 t.ha^{-1}, which corresponded to 1,150 to 1,550 m a.s.l. On the other hand, for LGS > 195 days, the attainable yield was much larger (37.6 ± 8.4 t.ha^{-1}), with a narrow elevation range: 2,850 to 3,200 m a.s.l. Consequently, these calculated values falling outside the optimum LGS range thus represented conditions that were not realistic for potato growth variables.

In spite of the range of elevations in the region and its consequences for weather and crop variables LGS and LAI, the modelled potato yield was rather insensitive across a wide range of elevations (1,600 m – 2,700 m a.s.l.) and with high topography model resolution. This raises the question whether high-resolution modelling is actually required to model potato yield and related variables reliably. This is discussed in the following section.

4.3. Compensating effect: the role of length of growing season and LAI

The sensitivity analysis performed in section 3 shows that temperature and precipitation had opposing behaviour to the elevational changes. Our results indicated that at higher elevations the lower temperature led to higher yields, while the increased precipitation decreased yield. Excess precipitation above the maximum moisture holding capacity of the soil was directly proportional to the soil nutrient leached (YL05). The opposing impacts of temperature and precipitation on yield thus compensated each other. In order to further quantify and explain this behaviour, we studied whether the opposing and non-linear effects of the meteorological variables offset each other in the crop growth simulation (Figs. 3 and 7) by performing the following experiment:

1) We took the weather data calculated in the fine resolution domain for the Chencha site in 2006, taking the climatologically normal *belg* season as reference case (control).
2) We substituted a weather variable (*i.e.*, T_{min}, T_{max}, Precp (precipitation), SW↓ or VPD) or pair of weather variables (*i.e.*, T_{min} and T_{max}, T_{min} and SW↓, T_{min} and VPD, T_{min} and Precp, T_{max} and SW↓, T_{max} and VPD, SW↓ and VPD, Precp and T_{max}, Precp and VPD or Precp and SW↓) in the fine resolution domain for its counterpart in the coarse resolution domain and modelled a new potato yield, combining the substituted weather variable(s) with the ones in the fine resolution domain. See more descriptions in TableS14.

Table 4 summarises the yield difference between the control run and the sensitivity experiment. The first row/column (values in brackets) shows the difference between the average weather variable in the coarse resolution domain and that of the fine resolution domain during the growing season. The remainder of the cells indicate the change in yield (*i.e.,* yield driven by the new weather combination minus the control run value in the fine resolution domain).

Our analysis demonstrated that the yield decreased by 7.3 t.ha^{-1} when T_{min} in the fine resolution domain was replaced by the 9.0 °C warmer T_{min} in the coarse resolution domain. Similarly, the yield decreased by 4.8 t.ha^{-1} when T_{max} was warmer by 8.5 °C than the fine resolution domain combined with the fine resolution domain's other weather variables. When T_{min} was simultaneously varied with precipitation or any other variable, the decrease in yield was also significant (5.0 to 7.9 t.ha^{-1}). In contrast, the yield increased by 12.1 t.ha^{-1} when precipitation that was lower by 4.3 mm.d^{-1} than the fine resolution domain was substituted. We hypothesise that this yield increase was due to the relationship between precipitation and nutrient leaching included in the GECROS model.

Table 4
Weather variable (diagonal cells) or a combination of two variables (row × column) of the coarse resolution domain that replaced the corresponding variable(s) in the fine resolution domain (control). The values in the brackets show the difference in the average weather conditions between the variable in the coarse resolution domain and the control conditions during 2006 *belg* growing season. The numbers in the cells indicate the difference in yield calculated between a sensitivity experiment the control run in t. ha^{-1}. The *compensating effect* experiment matrix shows 15 model experiments for the Chencha station during *belg* 2006.

Variables from coarse resolution domain that replaced those in the fine resolution domain	**T_{min} (+ 9.0 °C)**	**T_{max} (+ 8.5 °C)**	**Precip (-4.3 mm.d^{-1})**	**SW↓ (+0.9 MJ.m^{-2}.d^{-1})**	**VPD (+0.5 kPa)**
T_{min} (+ 9.0 °C)	−7.3	−7.9	−5.0	−7.3	−6.0
T_{max} (+ 8.5 °C)		−4.8	6.2	−3.8	−2.2
Precip (-4.3 mm.d^{-1})			12.1	12.0	11.9
SW↓ (+0.9 MJ.m^{-2}.d^{-1})				0.9	0.9
VPD (+0.5 kPa)					0.7

In the case where precipitation was combined with SW↓ or VPD, yield increased by ~ 12.0 t.ha^{-1}. The sensitivity experiments indicated that precipitation (+12.1 t.ha^{-1}) was the variable that had the largest influence on potato yield, followed by T_{min} (-7.3 t.ha^{-1}) and T_{max} (-4.8 t.ha^{-1}).

Regarding how the key meteorological actors offset each other in calculations of yield, we found that the increase in yield due to decreased precipitation was mainly offset by the simultaneous decline in yield because of increased T_{max} and T_{min} in the coarse resolution domain. Since this compensation occurred in both domains (with coarse and fine resolution), the potato yield modelled turned out to be comparable. However, in analysing the results for other key variables, we found that LGS and LAI in the fine resolution domain were 120 days and 3.02, respectively, whereas the values at the coarse resolution domain were LGS and LAI 59 days and 1.35, respectively. At the highest locations, the lower SW↓ and the temperatures (because of the increased cloudiness) induced a longer LGS, which explains why the yield was significantly greater at these locations. The sensitivity experiment on SW↓ showed that the potato yield and LGS decreased as the SW↓ increased (Fig. 3). As a remark, increases in SW↓, T_{max} and T_{min} decreased the LGS and LAI, which also offset yield. Our findings showed that, although we obtained similar results for the potato yield independent of the resolution of topography, there were important differences in the meteorological variables and in the key crop variables related to the calculation of the potato yield. These are discussed in the following section.

5. Discussion

Based on our findings, Fig. 8 integrates and summarizes the influence of the meteorological variables (as function of elevation) on simulated crop yield and related variables. In general, variations in the meteorological variables with elevation led to an increase in potato yield from 12.7 t.ha^{-1} in the lowlands to 37.6 t.ha^{-1} in the highlands as averaged over 10 *belg* seasons. However, the impact of elevation on the meteorological variables acted differently on the crop integrators (namely LGS and LAI) and on their direct impact on crop yield. As a result, and in the specific region under study, whose elevation ranged from 1,600 to 2,700 m a.s.l. the crop yield was almost constant with height, with a calculated attainable yield of 20.7 ± 4.1 t.ha^{-1} (Fig. 7).

The sensitivity analysis discussed in the previous section showed that there was a strong compensation effect in what determined calculated yield. Yield increases due to one meteorological variable were offset by decreases by another variable. The weather variables (SW↓, T_{max} and T_{min}) and yield were all interrelated by the crop integrators as shown in Fig. 8, based on the results obtained in the fine resolution domain (Figs. 3 and 7).

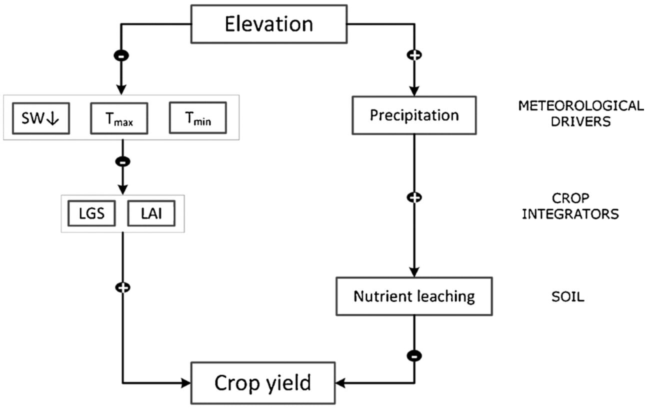

Fig. 8. The role of elevation and meteorological crop drivers in the attainable crop yield in region-II of Fig. 7. The key integrating matrices such as LGS and LAI relate the SW↓, T_{max} and T_{min}. Precipitation may influence the soil model by nutrient leaching. The crop integrators and nutrient leaching connect meteorological crop drivers and crop yield. The positive sign indicates a positive correlation whereas the negative sign shows a negative correlation.

A representative example is that an increase of temperature by 8.8 °C (as compared to the fine resolution domain) in the coarse resolution domain during the growing season led to a reduction in yield of up to 35% (of 22.3 t.ha^{-1} in the fine resolution domain) at the Chencha station during the 2006 *belg*. This reduction was associated with a 51% decrease in the LGS and a 58% decrease in the LAI. The opposite behaviour was found for precipitation, which was 4.3 mm.d^{-1} less than in the fine resolution domain and led to an increase in the attainable yield of 54% (relative to the fine resolution domain). This increase may be associated with more nutrients becoming available to the plant, since there was less leaching due to the reduction in precipitation (YL05). Compared to the other meteorological variables, the crop integrators were independent of changes in precipitation. This contrasting meteorological effect resulted in almost constant crop yield along the Gamo Highlands transect (region-II) in Fig. 7. Our results indicated that in the region, the yield enhancement was the result of a longer growing season and larger LAI driven by the lower temperature and possibly by more nutrient leaching due to higher the level of precipitation at greater elevation. In the lowlands (region-I) and in the most elevated zone (region-III), yield increases were mainly explained in terms of lower temperatures along the mountain transect.

Our results indicated that the prescribed topography had a major impact on the meteorological crop drivers. Although the results obtained with the finer resolution domain showed an improvement of the model results for key crop driver variables like T_{max} and T_{min}, there was no direct improvement for the individual meteorological variables. This was particularly relevant to the daily precipitation, for which the results from the coarse resolution domain matched the available observations better than those of the fine resolution domain, although the topography was very smooth in the coarse resolution domain. Our findings corroborate other studies that show that the WRF model is not very successful in correctly predicting the frequency and location of precipitation (Lunde et al., 2013) around Arba Minch. Improving the accuracy of forecasting daily precipitation, and more specifically, the onset and duration of rainfall during the growing season, is therefore a priority. This will require a complete analysis of the sensitivity of the model results to the representation of physical processes in this tropical, mountainous region. To be capable of determining the best combination of physical parameterization, the model validation will require more measurements of the spatiotemporal variability of the meteorological and crop data in situ and may benefit from adding remote-sensing observations. The wide range of elevations and the strong diurnal cycles in weather require meteorological observations to be taken hourly and at shorter spatial interval (~ 3–5 km).

It is also important to analyse the connections between the meteorological crop drivers and the LGS and LAI. As Fig. 8 shows, the decrease with elevation of the variables SW↓, T_{max}, and T_{min} led to a longer LGS period, as pointed out by (Peiris et al., 1996; van De Geijn and Dijkstra, 1995) and higher LAI, whereas precipitation has no effect on these two crop variables (Fig. 3). An accurate calculation of LGS related to the onset of precipitation is crucial to obtaining realistic values for potato yield and related variables (FAO, 2008; Harper, 1963).

The counteracting effects of temperature and precipitation in yield calculation demonstrate the need to prescribe soil moisture and elevation in fine resolution domains. Our findings show that doing so enables us to provide the best estimates of meteorological and crop variables. For the two crop integrators shown in Fig. 8, the LGS and LAI values calculated in the fine resolution domain are 120 days and 3.02 m^2/m^2. These are more realistic values than those calculated using the coarser resolution domain: 59 days for LGS and 1.35 m^2/m^2 for LAI. This improved consistency in the calculation using the finer resolution domain is also found for carbon allocation at harvest (attainable yield average over 10 *belg* periods): tuber yield (22.3 t.ha^{-1} in the fine resolution domain versus 22.3 t.ha^{-1}), stem mass (20.0 versus 4.5 t.ha^{-1}), leaf mass (4.4 versus 2.0 t.ha^{-1}) and root mass (2.7 versus 4.1 t.ha^{-1}).

Considering the sensitivity of meteorological and crop dynamics to elevation and the domain resolution, it is also necessary to perform projections of crop growth and yield for different scenarios of future climate. Haverkort and Struik (2015) suggested that potato production will be shifted to northern latitudes all over the world. On the one hand, in tropical highlands like the one under study here, global warming will reduce yield and could force potato production areas to move to more elevated locations where less arable land is available. On the other hand, a rise in precipitation in the future may reduce yields and shift the potato-growing zone to lower elevations, but this will require a detailed analysis of the relationship between nutrient leaching and precipitation. This makes crop growth difficult to predict in a changing climate. Furthermore, scenarios that include greater amounts of precipitation, T_{max} and T_{min}, in the future could increase cloudiness, atmospheric and soil moisture, which could result in a greater loss of potato production due to increases in insects and other pests (Tufa, 2013).

6. Conclusions

We investigated the effect of representation of elevation on the meteorological variables that drive the dynamics of potato growth. The region area studied is the Gamo Highlands in Ethiopia, which is situated in a tropical region characterised by a complex topography and consequently high spatial variability in meteorology. To this end, we applied a modelling framework that integrates meteorology and crop dynamics. We used high-resolution weather data to feed an advanced crop model and modelled potato growth over 10 years (2001–2010), and employed observations from two weather stations in the Gamo Highlands (located at 1,212 and 2,632 m a.s.l.) to validate the weather variables modelled.

Our numerical experiment used two domains with different horizontal resolution, both centred around Arba Minch using the Weather Research and Forecasting model (Skamarock et al., 2005). The first has a coarse resolution domain, *i.e.,* 54 km × 54 km, and the second has a much finer spatial resolution, *i.e.* 2 km × 2 km. In the fine resolution domain, an altitudinal difference of nearly 2,500 m is much better is much better resolved. In order to be consistent with the fine spatial resolution meteorological model domain, we also used high-resolution (1 km × 1 km) soil properties from the ISRIC database (Leenaars et al., 2014). A key aspect of our methodology is thus consistency in using high-resolution and hourly weather data as the main inputs to the state-of-the-art, eco-physiological crop model GECROS (Genotype-by-Environment interaction on CROp growth Simulator) over the complex terrain (Yin and van Laar, 2005). We performed a systematic sensitivity analysis on how weather variables influence crop dynamics. The 10-year study can be regarded as covering a sub-climatological period that enabled us to obtain robust and representative statistics.

Our first question was: how do weather and climate vary as a function of local topography, and how does it affect potato crop growth variables and yield? The major atmospheric crop drivers, the incoming short-wave radiation, precipitation, and maximum and minimum temperatures displayed a wide range of spatial variability. The SW↓ exhibited a non-linear reduction with height due to enhanced cloudiness. Precipitation increased exponentially across elevation, whereas temperature dropped linearly with ∼ 6 °C per km. Combined together, these atmospheric crop drivers influenced potato crop growth and led to an increase in LGS, LAI and the attainable potato yield as elevation increased. In analysing the 10-year modelled *belg* season weather data, we found large inter-annual variations in both observations and the modelled data. When we compared the results obtained by the coarse and the fine resolution domains, we also found large differences associated with cloud formation and its intensity. For SW↓ and precipitation in particular, the fine resolution domain was on average 22.7 W.m^{-2} larger and 2.7 mm.d^{-1} wetter than the coarse resolution domain over the 10-year period.

In spite of the differences due to different elevation and domain resolutions, the simulated attainable potato yield during the 10-year was comparable for the coarse and fine resolution domains (21.7 ± 3.2 and 22.1 ± 5.7 t.ha^{-1} respectively) at the location of the Chencha station. However, the results were different when we analysed other representative crop variables. Our findings revealed that the fine resolution domain had more realistic values of LGS (90–150 days) as suggested by FAO (2008) and LAI (3.0–5.4) as indicated in Harper (1963) as compared to the much lower values obtained using the coarse resolution domain.

Our second question was: does elevation enhance or lower the magnitude of key crop variables such as the length of the growing season (LGS), canopy development, carbon allocation to different parts of the plant, leaf area index and yield, and their interactions? The accurate representation of elevation in the finer resolution domain enabled us to identify the following relationship between elevation and attainable yield: a linear increase (region-I) between 1,100 to 1,500 m a.s.l., a steady-state (region-II) between 1,600 to 2,650 m a.s.l. and again a linear increase (region-III) between 2,950 to 3,200 m a.s.l. in yield. From the perspective of potato growth, region-I is not suitable for potato, as it is too warm and dry; region-II is the major potato production belt in the Gamo Highlands and region-III is used for potato cropping although it requires a much longer LGS than region-II.

We have discussed two of the above findings in depth: (a) the similarity in potato yield calculated using both the coarse and fine resolution domains (question 1) and (b) the existence of a region (region-II) with almost constant yield in spite of the wide elevation range (question 2).

In both cases, our analysis revealed that there was a *compensating effect* in the meteorological variables in the yield calculations that depended on the sensitivity of yield to meteorological variables. More specifically, the reduction in SW↓ and temperature with elevation had a positive effect on yield (Resop et al., 2014), unlike an increase in precipitation, which may have had an indirect negative effect on yield because increased precipitation led to an increased nutrient leaching (Yin and van Laar, 2005). Superimposed on these offsetting effects, but playing a key role, the dependence of LGS and LAI on meteorological variables that vary strongly with elevation needs to be taken into account. In view of the interrelationships between the meteorological and potato crop growth variables in regions of complex terrain, we recommend the use of meteorological model data with high spatial (∼2 km) and temporal (sub-daily) resolutions, which represent differences in elevation well, in order to adequately simulate not only crop yield but also intermediate crop dynamical processes.

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Appendix Supplementary material.

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agrformet.2018.07.009.

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