Full Length Research Paper

Growth analysis and modelling of CIP potato genotypes for their characterization in two contrasting environments of Burundi

D. Harahagazwe[1]*, J. F. Ledent[2] and G. Rusuku[3]

[1]Institut des Sciences Agronomiques du Burundi (ISABU), P. O. Box 795 Bujumbura, Burundi.
[2]Unité d'Ecophysiologie et Amélioration Végétale, Faculté d'Ingénierie biologique, agronomique et environnementale, Université Catholique de Louvain, Place Croix du Sud, 2 Box 11, B-1348 Louvain-la-Neuve, Belgium.
[3]Institut de Recherche Agronomique et Zootechnique (IRAZ), P.O. Box 91 Gitega, Burundi.

A version of LINTUL-POTATO model was used in the context of highlands and lowlands of Burundi to calculate a potential yield as limited by meteorological factors only. This potential yield was compared to the yields obtained in field experiments conducted in the respective areas using potato genotypes from International Potato Center (CIP) reported to be adapted to tropical conditions. Deviations of observed yields from potential yield varied with genotype and location. These deviations were used to characterize the behaviour of genotypes and their adaptation to the region. The field observations confirmed that high temperatures decrease the tuber yield and harvest index and increase shoots weight at final harvest and the model simulated correctly these effects. The large variation of yield deviations showed that the genotypes differed widely in the response of their yield to temperature. But other factors than temperature such as differences in sensitivity to diseases, occurrence of pests, fertilization etc., may have played a role. Genotypes suitable for highlands and others suitable for lowlands were identified. Selected genotypes for lowlands (where temperatures are 8°C higher compared to highlands) could be also of great use even in cooler areas where temperature is expected to rise due to global warming. The simulation model showed the extent of further losses of potential yields in lowlands if drought stress is not addressed properly.

Key words: Simulation, LINTUL-POTATO model, CIP potato genotypes, contrasting environments, Burundi.

INTRODUCTION

In Burundi, potato (*Solanum tuberosum* L.) is cultivated in highlands. To our knowledge, not a single potato field cultivated for commercial purpose has been reported in the lowlands of Burundi so far. Also, most of the studies conducted on the potato crop in Burundi were carried out in highlands that is, in the region where potatoes are traditionally grown. From 2005 to 2008, a series of field trials in two contrasting environments, including lowlands were conducted. Those experiments generated a database that could be used to test crop growth models.

Simulation models are good tools to integrate physical and physiological characteristics from experimental work in order to explain the system and test new hypotheses (van Ittersum et al., 2003). Many crop growth models exist around the world but one of the model families used for potato crop is LINTUL-POTATO developed by Kooman and Haverkort (1995a). This model belongs to the family LINTUL (Light INTerception and UtiLization Simulator) developed by Spitters and Schapendonk (1990) and based on the pioneer work of Monteith (1977). Our choice was based on the fact that versions of this model have been widely used through the world including Africa and that information on the code of the model is readily available (Haverkort and MacKerron, 1995; Kabat et al., 1995; Kooman, 1995; van Ittersum

---

*Corresponding author. E-mail: dharahagazwe@yahoo.fr.
Tel: 00258 823565543.

Table 1. Description of experimental locations and experiments.

Parameter	Highland		Lowland	
	Gisozi	Ryansoro	(Mparambo)	
Season	Dry	Dry	Dry	
Latitude (S)	3°34'	3°47'	2°50'	
Longitude (E)	29°41'	29°46'	29°04'	
Altitude (masl)[a]	2091	1833	892	
PAR[b] ($MJ.m^{-2}.d^{-1}$)	9.04	-	8.62	
Climate type (after Köppen)	Cw	Cwbi	$(Aw_4)s$	
Soil type	Alluvial	Colluvial and alluvial	Hygro-xerokaolisols	
Irrigation (whole season)	No	No	Yes	
Usual rainfall (mm)	1443	1427	900	
Seed source	ISABU	ISABU	ISABU	
Year of experiment	2007	2007	2006	2007
Average temperature (°C)[c]	16.9	19.4	25.1	26
Minimum temperature[c]	11.3	15	19.0	21.5
Maximum temperature[c]	22.5	23.8	31.1	30.5
Planting date	12/7/07	18/7/07	29/6/06	10/8/07
Day[d] of planting	193	199	180	222
Harvest date	13/12/07	12/12/07	11/10/06	23/11/07
Day[d] of last harvest	339	338	284	327
Experimental season length (days)	154	147	104	105

[a]masl, Meters above sea level. [b]Figures were obtained by using FAO data (FAO, 1984b). PAR in Mparambo may indeed be considered as similar to the radiation recorded at Bujumbura according to its geographic position. [c]Average air temperature during the growth cycle of the experiments. [d]Day of the year.

et al., 2003). Also the model is relatively simple to use (Condori et al., 2010).

By conducting this study, we wanted to obtain a better understanding, in the context of Burundi, about the three different levels of production as described by van Ittersum et al. (2003): potential, attainable and actual yields. According to these authors, yield levels are related to a hierarchy of growth factors. Potential yields are defined as the yields determined by radiation intensity, carbon dioxide concentration, temperature and genotypic characteristics of the crop. In a given environment, attainable yields are defined as the yields achieved in an environment without water and nutrients limitations. Actual yields are those obtained when water and nutrients limitations and growth-reducing factors (biotic and abiotic constraints) are taken into account. Since the potential yield is rarely achieved in field crops for any crop, actual yields correspond to just a fraction of potential production, ranging from less than 5 up to 60% (van Ittersum et al., 2003). Generally, attainable yields are half of the potential yields, irrespective of growing conditions (van Keulen and Stol, 1995b). The same authors stated that actual yields are closer to attainable yields in temperate climates than in tropical conditions.

We used a version of LINTUL based on LINTUL-POTATO in order to achieve three main objectives: (1) to determine the potential tuber yield of CIP materials in the lowlands and in highlands of Burundi where temperature differs drastically and quantify the impact of heat on this potential yield; (2) to compare simulated values of potential yield to observed values of actual yield obtained in variety trials in order to characterize genotypes productivity and their adaptation to the two contrasting environments, and (3) to obtain some first estimation of the relative effect of drought stress in lowlands conditions where the evapotranspiration is higher than in highlands.

It is worth mentioning that all these three specific objectives contribute to a larger initiative aiming at the introduction of the potato crop in the agrarian systems of lowlands of Burundi. Due to heat, potatoes are not grown so far in those agro-ecological conditions.

MATERIALS AND METHODS

Experimental sites

The trials were conducted in three different locations, namely Mparambo for lowlands, and Gisozi and Ryansoro for highlands as described in Table 1. Mparambo (892 masl) is located in the North West of the Imbo region and belongs to Rugombo commune in the province of Cibitoke. Imbo is one of the eleven natural regions of Burundi and represents the lowest zone of the country. In Mparambo, the trials were carried out in 2006 and 2007 on a research station owned and managed by ISABU (Institut des

Table 2. Parentage of the potato genotypes used in the trials (CIP, 2011).

Clone number/variety	Pedigree
388611.22	720091 x 385305.1
388972.22	XY.20 x 377964.5
390663.8	SERRANA x XY.14
395193.4	C91.612 x C92.030
395194.9	NA
Ndinamagara	NA
Victoria	378493.915 x BULK PRECOZ
Ruhanyura	380086.3 x BULK MEX

NA, Not available.

Sciences Agronomiques du Burundi). The 2006 trials conducted in Mparambo suffered from floods caused by irrigation water because the plots were badly drained. The second location where we conducted our trials in 2007 is Gisozi (2091 masl). It is one of communes of Mwaro province and is the site of the oldest research station of ISABU. Created in 1929, the station is situated in the South East of Mugamba which is the most elevated region of the country with an altitude ranging from 2000 to 2670 m (Heha Mountain). The last location is Ryansoro and the trials were conducted in a farmer's field in 2007. Ryansoro (1833 masl) is located between Bututsi and Kirimiro regions. On this site, trials were installed on the edges of a large river called Gitanga.

As shown in Table 1, the study was conducted in two contrasting environments, in terms of temperature, Gisozi and Ryansoro for highlands and Mparambo in the lowlands. As expected, the average temperature was higher in lowlands (25.1 to 26°C) than in highlands (16.9 to 19.4°C). Due to this difference of temperatures the lowlands are expected to be more exposed to drought than the highlands due to higher evapotranspiration. We avoided the effect of drought in our trials even when we planted in dry seasons through the application of water at one-week intervals in Mparambo (lowlands), whereas the trials conducted in highlands were installed in marshlands.

Genotypes used

Five clones from CIP considered to be promising for heat tolerance (CIP01, CIP02, CIP03, CIP04 and CIP05) were planted in all our experiments. The CIP code numbers of those genotypes and in parenthesis the corresponding simpler codes we used for facility are as follows: 388611.22 (CIP01), 388972.22 (CIP02), 390663.8 (CIP03), 395193.4 (CIP04) and 395194.9 (CIP05). All of these genotypes were reported to be heat tolerant and virus resistant (Bonierbale from CIP, personal communication). In addition to clones, we also planted three varieties which have been on release in Burundi for several years. Those varieties are Ndinamagara (also called Cruza 148), Victoria (381381.20) and Ruhanyura (382171.4). As for clones we used simpler names for those varieties: NDINA standing for Ndinamagara, RUHA for Ruhanyura and VICTO for Victoria. Unlike the two last varieties cited, NDINA is known to be a late maturing variety. It is also the most cultivated potato variety in the country. Introduced for the first time in 1998 (Harahagazwe, 2006), VICTO is the most popular variety in Uganda where it was released for the first time in September 1991 (Low, 1997). RUHA, a variety with high yielding ability, was released at Buyengero in 2003 (Harahagazwe, 2003). Table 2 provides the parentage for most of the genotypes used in this study.

Experimental design and weather data collection

All experiments were laid out in a Randomized Complete Block Design (RCBD) with three replicates. Each plot contained 30 plants into two rows of 15 plants each for each of the eight potato genotypes. For both trials, we used a spacing of 80 cm between rows and 30 cm between plants within rows. Thus, plant density was 4.17 plants m^{-2}. Plants of the variety NDINA were used as a border for the experiments. Plants were protected against Late Blight caused by *Phytophthora infestans* (Mont.) de Bary by spraying Ridomil Gold MZ 68WP (Anonymous, 2007) and Dithane M-45 (Anonymous, 1998) in an alternated manner. Dimethoate (Anonymous, 1996) was also sprayed in order to control mainly aphids.

In crop modelling, weather is a key component, especially radiation and temperature. Therefore, temperature was recorded at one-hour interval by HOBO Data loggers installed at Mparambo and Ryansoro sites during the growing seasons. However, the Data logger at Ryansoro could not reach the end of the growing season due to technical problems which occurred one month before harvest. In Gisozi, we used the data recorded by the National Meteorological Station in that location. To characterize the temperature of the different sites, we used daily data recorded at 8:00 A.M. as daily minimum temperature and those recorded at 3:00 P.M. as daily maximum temperature. Those are the only temperature records which are taken daily by an agent at the station. The daily minimum and maximum temperatures were then used as inputs in the model.

To record radiation, we installed a HOBO Micro station logger in Mparambo on the fourth of August 2006. However, it stopped working on the 10th of October 2006 due to a technical failure. Therefore, we used in the model, for the whole growth cycle and for all experiments (seasons by locations), the daily average of Photosynthetically Active Radiation (PAR) of 9.1 MJ.m^{-2} calculated from the 2-month period of recording. Indeed, this value is close to the ones found in literature. In highlands (Gisozi), the annual average PAR is estimated to be 9.04 MJ.m^{-2}.d^{-1} against 8.62 at Bujumbura representing lowlands (FAO, 1984a).

Experimental data collection

Four harvests per cycle were conducted for each trial except at Mparambo where only two harvests were conducted in 2007. For every harvest, four plants per block were entirely removed from the soil and separated into foliage and tubers prior to weighing. Then, we weighed fresh tubers. In order to determine the dry weight of each organ, we sampled 1 kg of foliage and 1 kg of tubers. Every sample was divided into three sub samples of 200 g each to be dried up in an oven at 105°C for 72 h. Sub samples were cut into small pieces (shoots) or slices (tubers) prior to processing. The values obtained from experiments were compared to the simulated ones generated by the model as described hereafter.

Duration of plant growth was estimated from the emergence to the end of the crop growth defined as the stage at which all leaves are dead (Kooman et al., 1996). The same authors indicate that this cycle comprises three phases. The first phase (phase 1) starts when 50% of plants have emerged and ends with tuber initiation (TI). Starting with TI, phase 2 goes up to the end of leaf growth (or when 90% of assimilates produced daily are partitioned to tubers). The last phase (phase 3) is ended when the crop has completed its growth cycle. Visual observations of crop growth were based on digital photographs taken from an angle of 45°, and covering all genotypes, one by one, on a basis of 2-week interval from the emergence. Those images were used to determine the change of leaf colour during the maturing period and the death of the leaves, the dates of observation being registered in the memory card of

Table 3. LINTUL-POTATO model as described by Kooman and Haverkort (1995a).

Parameter	Equation
Daily total dry matter increment	$\delta W = PAR * F_{LINT} * LUE$
Light interception	$F_{LINT} = 1 - e^{-K*LAI}$
Leaf area growth	$LAI = LAI_o * e^{(R_L * \sum T_{LUE})}$ if $\sum T_{LUE} < 450ºCd$ or $LAI < 0.75$
Leaf area growth	$LAI = W_{lv} * SLA$ if $\sum TLUE \geq 450ºCd$ or $LAI \geq 0.75$
Daily growth of organs	$\delta W_i = P_i * \delta W$

the camera.

Despite the fungicides were sprayed, late blight was observed in highlands on two genotypes. Therefore, its severity was visually measured as the percentage of diseased shoots (stems and leaves) in comparison to the entire healthy plants for each plot. In lowlands, Fusarium Wilt was recorded by numbering the plants presenting wilting symptoms.

LINTUL-POTATO model as described by Kooman and Haverkort

Under LINTUL-POTATO, the daily dry matter increment (δW) in the situation of potential production, as shown on Tables 3 and 4, is the product of: (1) the incoming PAR, (2) the fraction of PAR intercepted by the foliage and (3) the efficiency of its use for dry matter production called light use efficiency (LUE). Some of the inputs we used to run the model were specific to our experimental conditions. Like in other tropical zones, the photoperiod is 12 h a day. As said earlier, the plant population density used was 4.2 plants m^{-2} for all experiments. The SLA (specific leaf area) used in the model were borrowed from other studies carried out in the same conditions: 0.027 $m^2 g^{-1}$ in highlands and 0.025 $m^2 g^{-1}$ in lowlands (Harahagazwe, 2003). The model was also run for 122 DAE (days after emergence) in highlands against 67 DAE (in 2006) and 84 DAE (in 2007) in lowlands to correspond to the local conditions of potato production. Due to the volume of activities to be conducted at the same time and the long distances between sites, it was not possible to define key parameters (genetic coefficients) for each genotype such as time to the tuber initiation and potential (maximum) tuber growth rate.

To obtain the cumulative amount of dry matter produced, the daily growth is integrated over the growing period, starting from emergence for shoots and tuber initiation for tubers. This crop model was first used for high and lowlands in order to predict the potential dry tuber yield, assuming environments with ample water and nutrients supply, and without pests, diseases and weeds (Kooman and Spitters, 1995b). In the second step, we included in the model for lowlands a coefficient for water stress on crop growth defined as a ratio between actual (T_A) and potential (T_P) transpiration. This ratio, called *fwt* in the model and this paper, is assumed to decrease linearly with soil moisture content (SM) from unity at critical soil moisture content (SM_{cr}) to zero at wilting point (SM_{wp}) as shown on Equation 1 (Driessen, 1986):

$$T_A/T_P = (SM - SM_{wp})/(SM_{cr} - SM_{wp}) \quad \text{with } 0 \leq T_A/T_P \leq 1 \quad (1)$$

For simulation purpose, we forced the value of coefficient *fwt* in the model to 1 (no drought) for calculation of potential yield and to 0.75 for a situation of moderate water stress. This submodule was not performed for highlands where soil water was available *ad libitum* during the whole growth cycle. We constructed our LINTUL model version in Excel spreadsheets where macros were developed in Visual Basic for Application (VBA, Excel). The governing equations

were found in the literature (Kooman, 1995; Kooman and Haverkort, 1995a) and translated into VBA. Some of these equations are presented above in this text. Some of those equations require numerical calculus methods because they can't be solved analytically (van Ittersum et al., 2003).

It is important to mention that for our work we considered that the model was already calibrated and validated by its authors (Kooman and Haverkort, 1995a) for tropical conditions, including Rwanda which is a neighbouring country to Burundi. Also, we did not at this stage attempt to introduce or modify genetic characters such as time to tuber initiation and maximum potential growth rate of tubers. Therefore, the model simulated the potential yield for a typical potato genotype, and the simulations were not supposed to reproduce the specificities of the different genotypes included in our study, but only to be used as a common reference to which the observed yields of the different genotypes could be compared. Deviations of observations from this common potential yield were used to characterize the varieties. These comparisons were based on the standard errors of differences between the means as illustrated by vertical bars in the figures.

RESULTS

Dry weight of plant organs over time in lowlands

Data collected from the trials conducted in lowlands allowed to generate graphs for cumulative dry matter growth for each plant organ (leaves, stems and tubers) as shown on Figures 1 and 2. The analysis of those graphs shows that dry matter weight from leaves per unit area did not differ significantly from dry matter of stems for all genotypes tested during the whole crop cycles except at harvest time for CIP02, CIP04 and CIP05 where leaves were more important than the stems. At harvest time, dry tuber weight per unit area for all genotypes was significantly higher than the weight of each of the other organs except in the case of CIP02, CIP05 and NDINA (Figure 1). Growth curves indicate also that tuber initiation was delayed in the case of clone CIP03 and variety RUHA (compared to other clones or varieties), no single tuber being yet formed at 27 days after emergence (DAE).

Due to less adaptability to hot conditions (Harahagazwe, 2006), and unlike what was observed in other genotypes, tuber weight of NDINA did not exceed the weight of each of the other organs during the whole crop cycle (Figure 1). For this variety, leaves and stems remained relatively important, in comparison with tubers,

Table 4. List of acronyms and parameters used in the model.

Acronym	Meaning	Unit
$\sum T_{LUE}$	Thermal temperature sum from emergence	°Cd
F_{LINT}	Light interception	
K	Extinction coefficient	
LAI	Leaf area index	$m^2.m^{-2}$
LAI_o	Initial leaf area index (estimated at 0.0155 × number of plants per m^2	$m^2.m^{-2}$
LUE	Average light use efficiency	$g.MJ^{-1}$
PAR	Photosynthetically active radiation	$MJ.m^{-2}$
P_i	Partitioning factor for organ i	
R_L	Relative increase rate leaf area (estimated at 0.012)	$m^2.m^{-2}.d^{-1}$
SLA	Specific leaf area of a new leaf	$m^2.g^{-1}$
W_{lv}	Dry matter of total leaves	$g.m^{-2}$
δW	Daily growth of dry matter	$g.m^{-2}.d^{-1}$
δW_i	Dry matter growth of organ i	$g.m^{-2}.d^{-1}$

Table 5. Observed dry tuber yield of the best genotypes obtained at different dates in the field trials.

Alt.	Experim.	Date (DAE)	Dry tuber yield (t.ha^{-1})								s.e.d.
			NDINA	CIP04	VICTO	CIP02	CIP05	CIP01	CIP03	RUHA	
Highlands	GIS07	86	10.1	7.9	7.7	7.6	-	-	-	-	1.155
		100	7.8	8.2	6.8	5.7	6.4	-	-	-	1.337
	RYA07	101	-	-	11.6	9.7	10.1	-	-	-	1.422
Lowlands	MPA06	39	-	-	-	-	-	2.5	-	-	0.437
		67	-	3.8	3.0	-	3.0	4.3	3.6	2.6	0.943
	MPA07	55	-	1.2	2.0	1.7	1.4	1.7	1.5	1.3	0.565
		69	-	2.8	3.3	-	3.1	2.4	3.7	-	0.628

Alt., Altitude; Experim., experiment; GIS07, Gisozi 2007; RYA07, Ryansoro 2007; MPA06, Mparambo 2006; MPA07, Mparambo 2007; DAE, Day after emergence. s.e.d., standard error of difference between genotypes means. Genotypes are shortened as in Figure 1. Dash means that the genotype doesn't belong to the group of best genotypes.

from the beginning to the end of the crop cycle (Figures 1 and 2).

Simulated versus obtained yields

In highlands, VICTO, CIP02 and CIP05 were always among the best groups for tuber weight – the best group being formed by the genotypes whose yield did not differ significantly from the highest yielding one - at different dates: 86 and 100 DAE for Gisozi and 101 DAE at Ryansoro. However, there was a delay in tuber bulking for CIP05 at Gisozi (Figure 3 and Table 5). NDINA and CIP04 also appeared to be suitable for low temperature conditions especially at Gisozi where they ranked first (10 t.ha^{-1}) and second (7.9 t.ha^{-1}) respectively at 86 DAE. The unexpected change in tuber performance of CIP04 from Gisozi to Ryansoro may be explained by Late Blight but the case of NDINA is still to explain. The remaining

genotypes (CIP01, CIP03 and RUHA) never belonged even once to the group of best genotypes in conditions mentioned above (Table 5). When averages across all genotypes are calculated, we find 7.6 t.ha^{-1} of dry tuber yield in highlands (Gisozi and Ryansoro) at final harvest time (100 to 101 DAE) against 14.3 t.ha^{-1} generated by the simulation model. This simulated tuber yield is closer to the one (15.9 t.ha^{-1}) found in simulation by other scientists in a similar environment to ours in terms of temperature (17°C) and photoperiod (Kooman and Haverkort, 1995a).In lowlands, CIP01, CIP03, VICTO, CIP04 and CIP05 produced more tuber dry matter than the other genotypes at final harvest of experiments carried out in 2006 and 2007 (Figure 3 and Table 5). Table 5 is based on the same results as Figure 3; it is given to facilitate the reading of the yield results. Figure 3 and Table 5 show that these five genotypes were already the best in tuber yield, together with CIP02, two weeks before final harvest in 2007. Among the other genotypes,
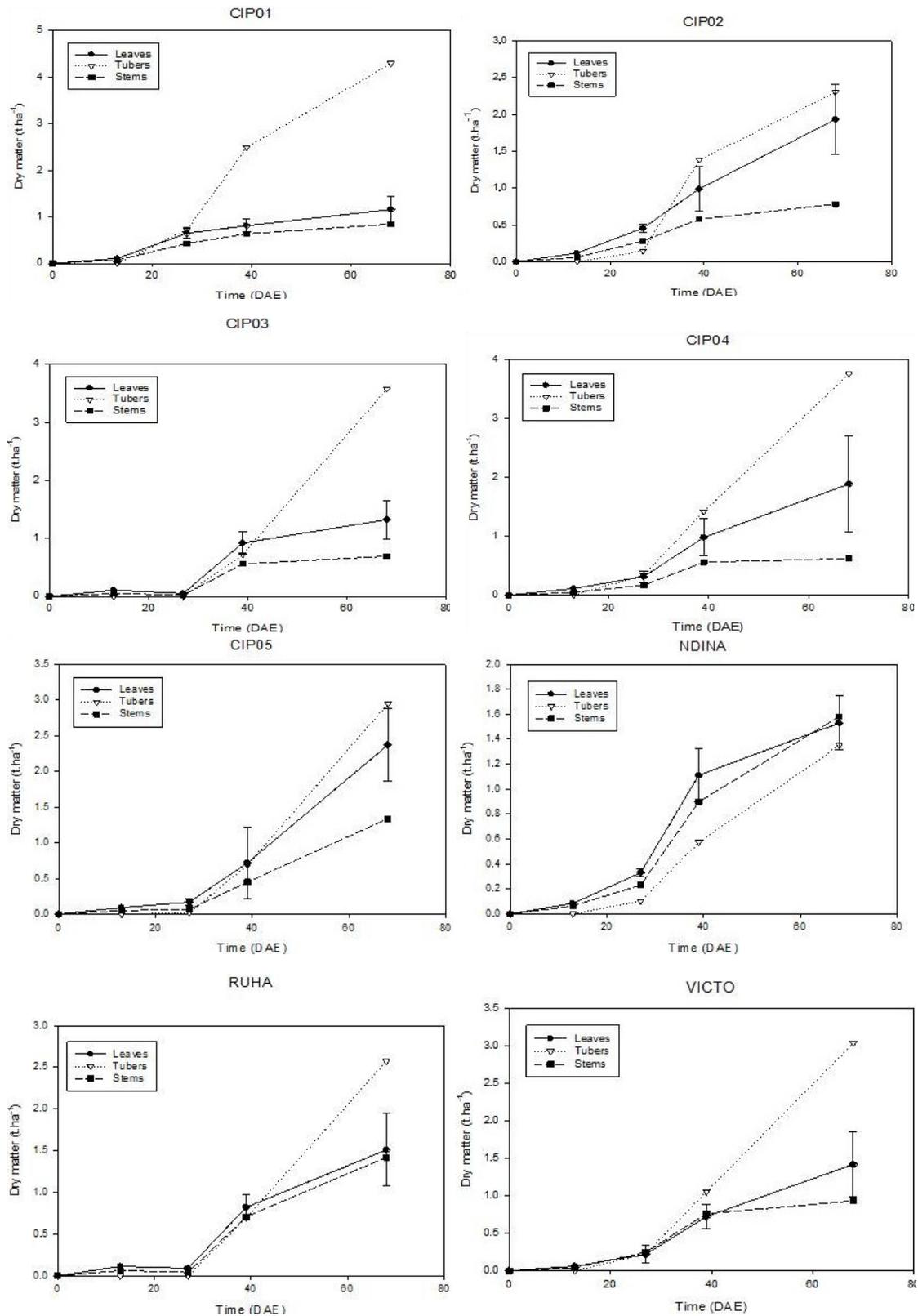
Figure 1. Cumulative dry matter weight per plant organ over time of the trial conducted in lowlands (Mparambo) in 2006. DAE stands for days after emergence. Vertical bars represent the standard errors of differences between means per plant organ. Genotypes are coded as follows: 388611.22 (CIP01), 388972.22 (CIP02), 390663.8 (CIP03), 395193.4 (CIP04), 395194.9 (CIP05), Ndinamagara (NDINA), Ruhanyura (RUHA) and Victoria (VICTO).

CIP01

CIP02

CIP03

CIP04

CIP05

NDINA
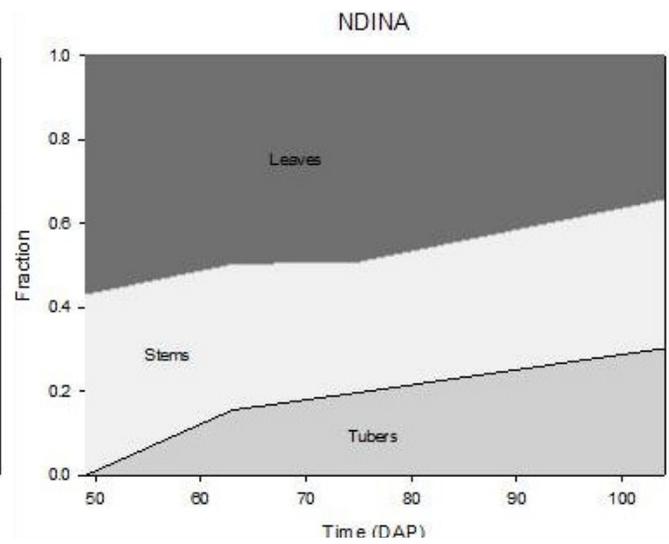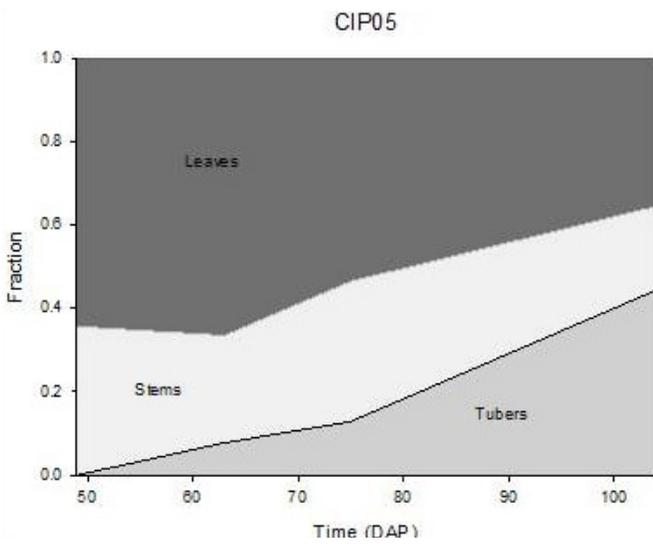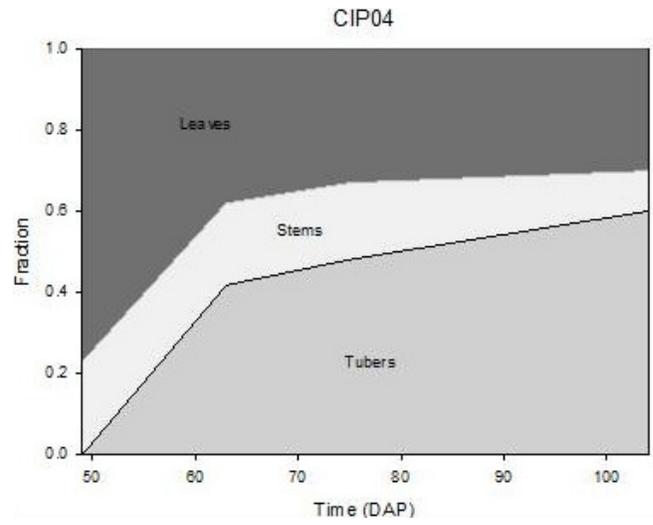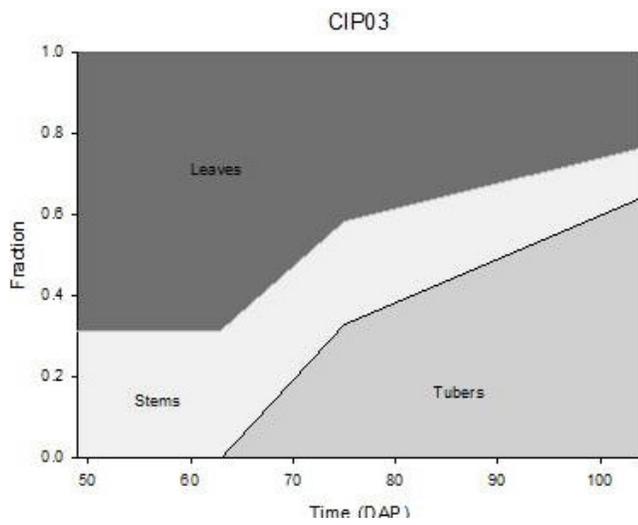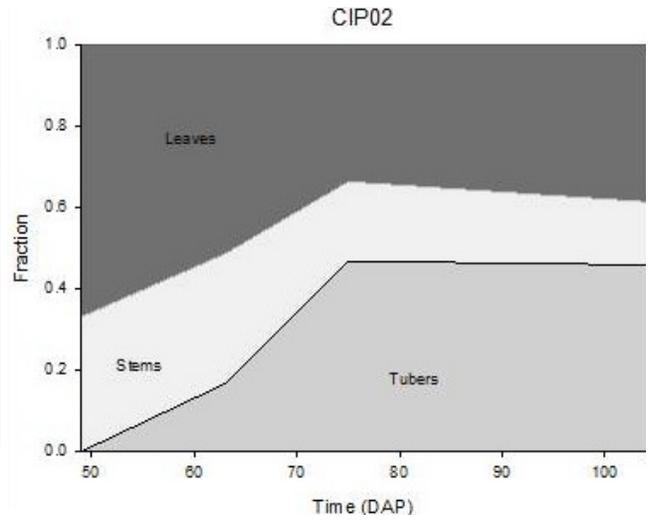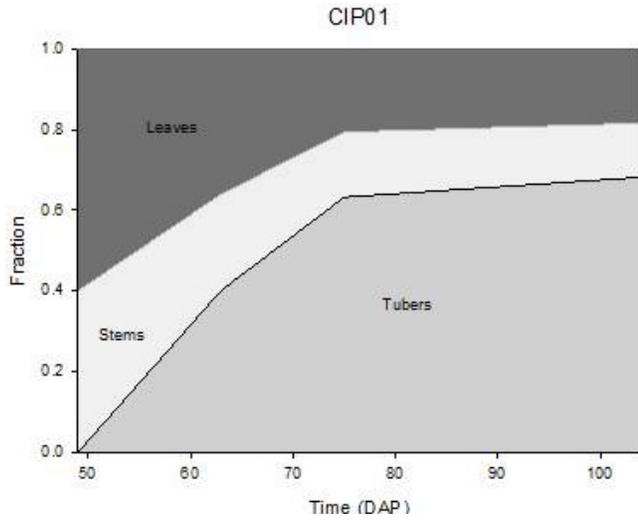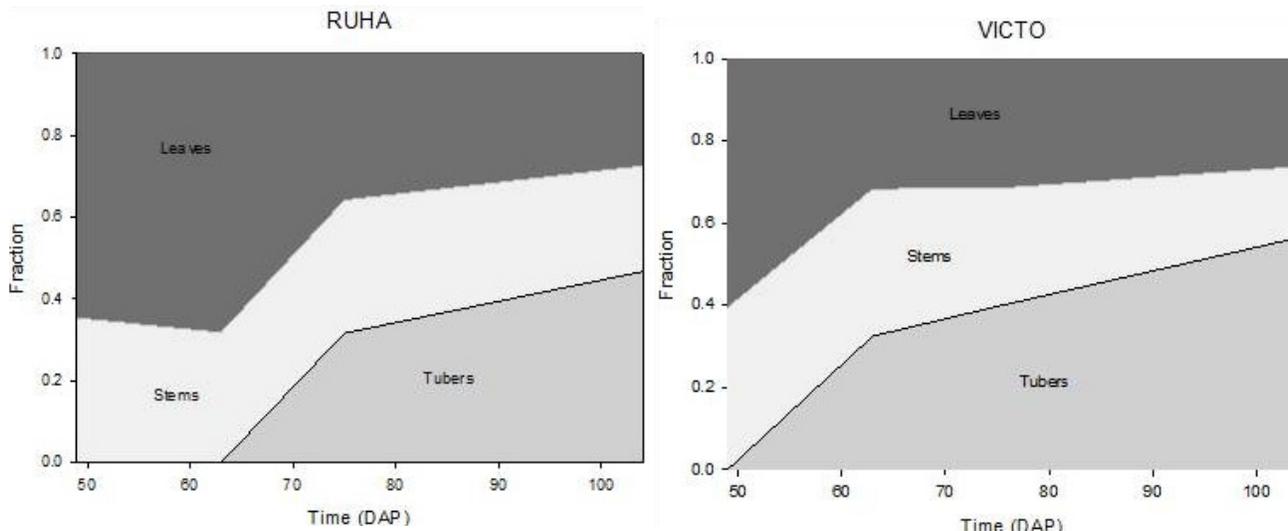
Figure 2. Schematic representation of the proportional distribution of the dry weight of the different plant organs relatively to total plant weight (without roots) for eight potato genotypes tested in lowlands (Mparambo) in 2006. DAP stands for days after planting. Genotypes are coded as follows: 388611.22 (CIP01), 388972.22 (CIP02), 390663.8 (CIP03), 395193.4 (CIP04), 395194.9 (CIP05), Ndinamagara (NDINA), Ruhanyura (RUHA) and Victoria (VICTO).
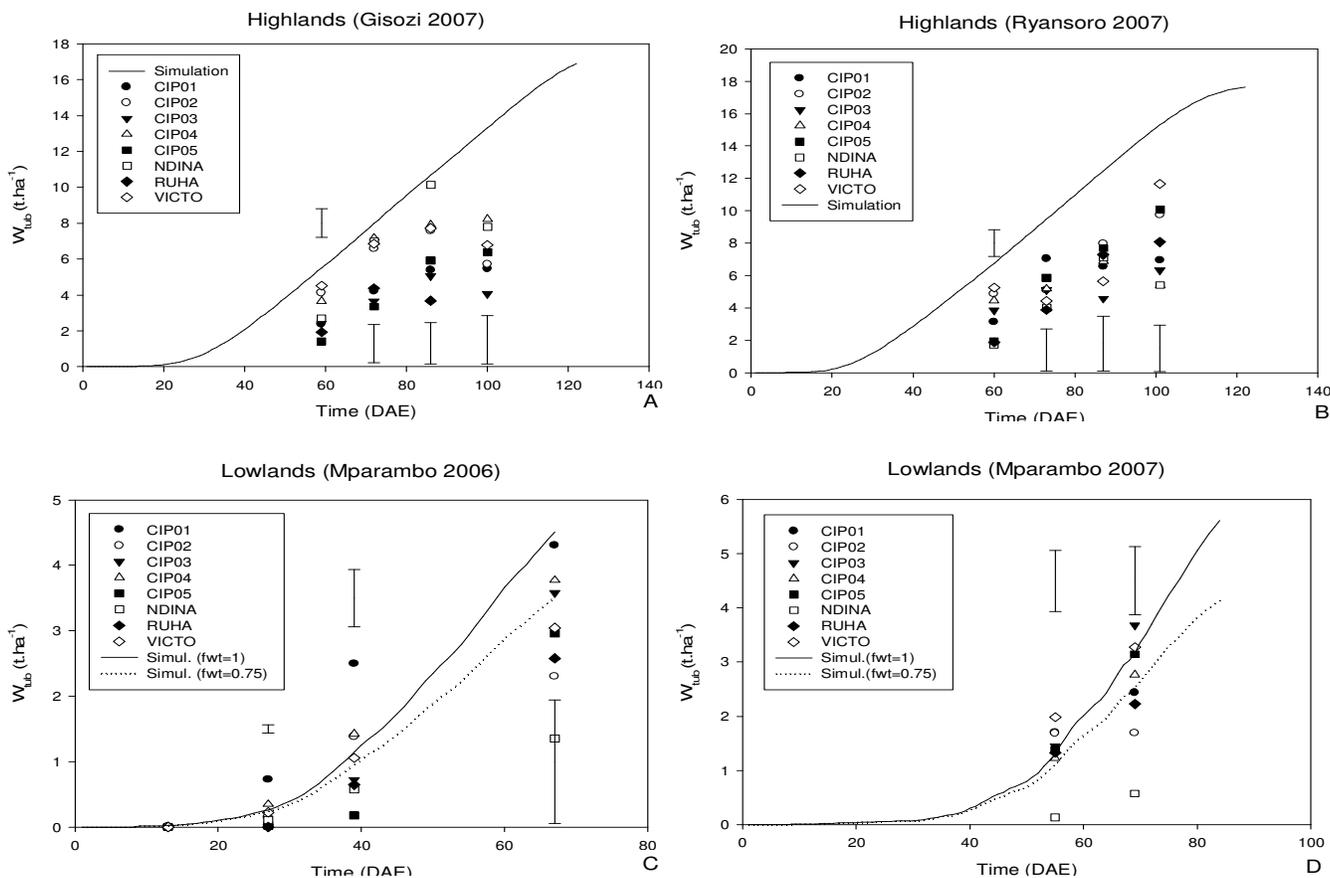
Figure 3. Simulated (solid and dotted line) and observed (scatter plot) values of tuber dry yield (W_{tub}) for eight potato genotypes tested in Burundi: highlands (A and B) and lowlands (C and D). Genotypes are coded as follows: 388611.22 (CIP01), 388972.22 (CIP02), 390663.8 (CIP03), 395193.4 (CIP04), 395194.9 (CIP05), Ndinamagara (NDINA), Ruhanyura (RUHA) and Victoria (VICTO). DAE stands for days after emergence and *fwt* for coefficient of drought stress. Vertical bars represent the standard errors of differences between obtained means at each date of observation.
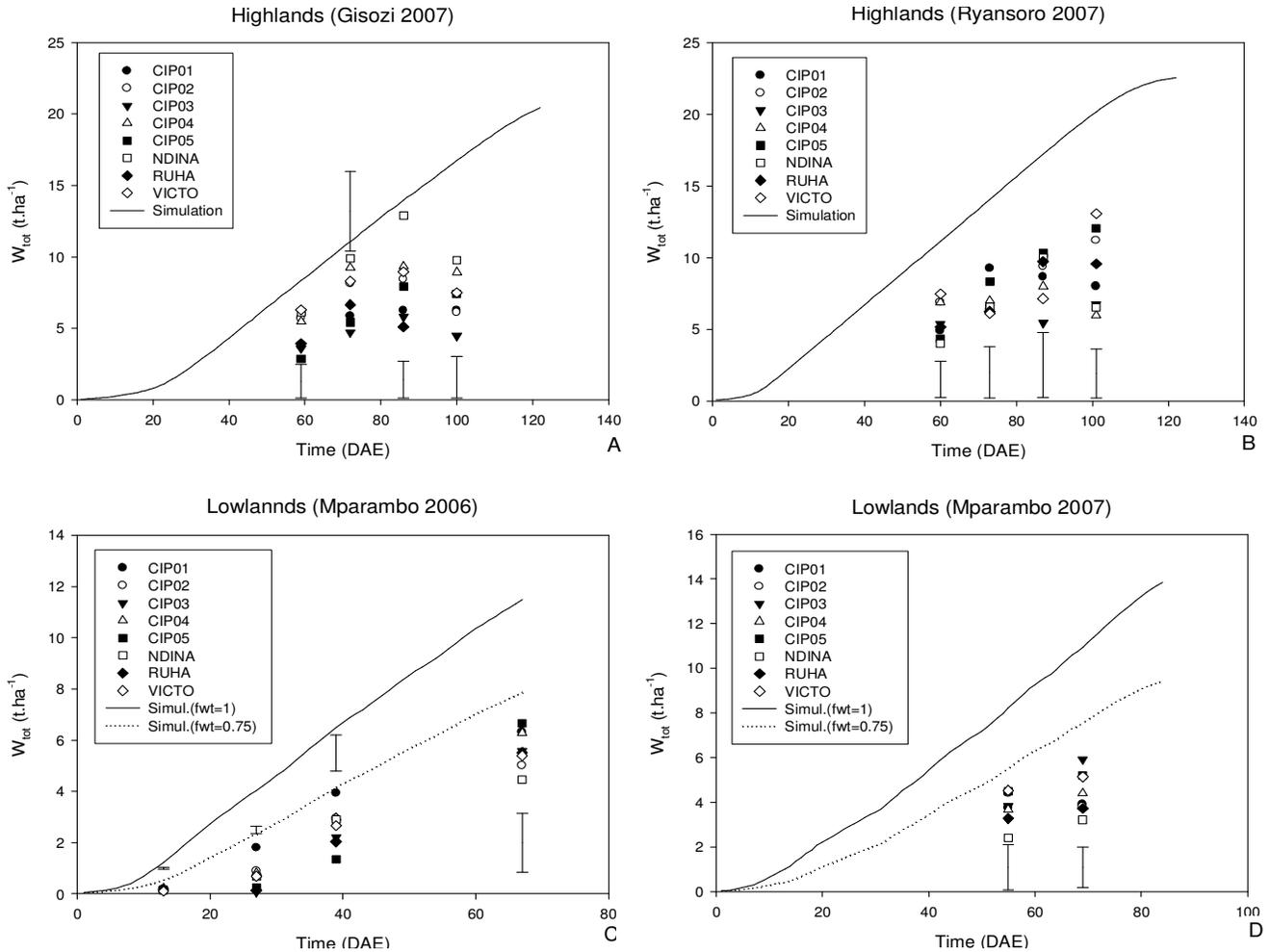
Figure 4. Simulated (solid and dotted line) and observed (scatter plot) values of shoots dry yield (W_{sht}) for eight potato genotypes tested in Burundi: highlands (A and B) and lowlands (C and D). Genotypes are coded as follows: 388611.22 (CIP01), 388972.22 (CIP02), 390663.8 (CIP03), 395193.4 (CIP04), 395194.9 (CIP05), Ndinamagara (NDINA), Ruhanyura (RUHA) and Victoria (VICTO). DAE stands for days after emergence and *fwt* for coefficient of drought stress. Vertical bars represent the standard errors of differences between obtained means at each date of observation.

CIP01 produced more dry tuber weight than the other genotypes at 39 DAE only in the experiment conducted in 2006 with an average yield of 2.5 t.ha^{-1}. Also, NDINA and CIP02 appeared not to be suitable for the lowland region with regard to the tuber productivity. They produced on average 1 t.ha^{-1} of tuber dry matter (mean of the annual yields at final harvests) for the former and the double for the latter. This statement could be extended to RUHA which ranked last in 2006 and penultimate in 2007 in the group of best genotypes (Table 5). At final harvest time (67 to 68 DAE), all genotypes tested in lowlands produced an average tuber yield of 2.7 t.ha^{-1} in terms of dry matter while the simulation model gave 3.8 t.ha^{-1}. Unlike in highlands, these yields (obtained and simulated) remain lesser than the yield (11.7 t.ha^{-1}) found by others with simulations at 25°C and under 11 h of photoperiod using their version of the LINTUL-POTATO model (Kooman and Haverkort, 1995a) but with slightly different inputs.

With regard to shoot dry matter production, NDINA and CIP05 were more productive than other genotypes at almost all dates of observation in highlands (Figures 4A and B). As in highlands, those genotypes produced heavy haulms in lowlands. This is an indication that they have very high potential in producing shoots wherever they are planted. Since the plants were sprayed with fungicides and insecticide, the shoots of genotypes did not show visual Late Blight diseases and pests' symptoms in highlands except for clones CIP03 and CIP04 whose shoots were destroyed at 75% by Late Blight three months after planting. However, in both environments (high and lowlands), small symptoms of Early Blight caused by *Alternaria* spp. were seen on leaves of all genotypes but with emphasis on NDINA. In lowlands, Fusarium Wilt was the most dominant disease observed in the fields but wilted plants were not taken
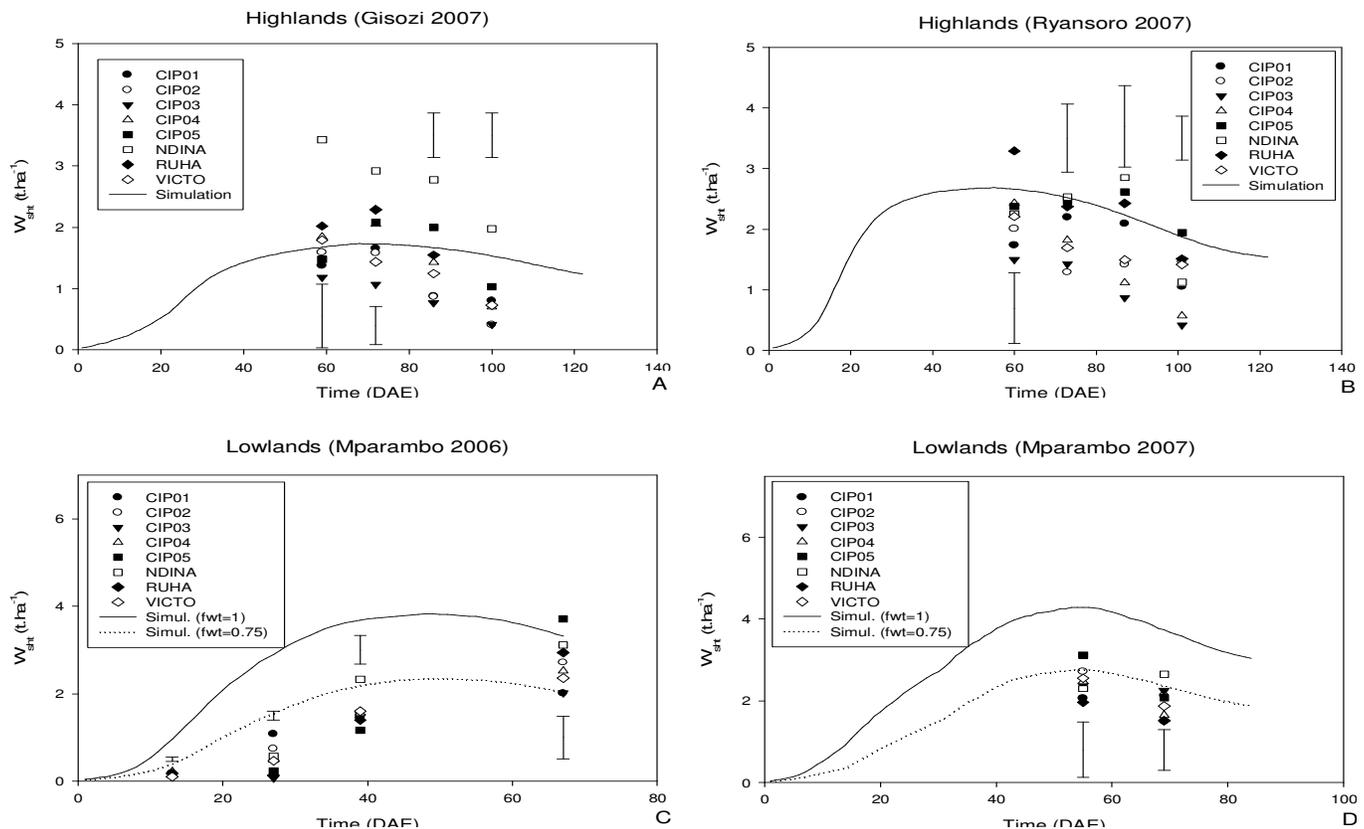
Figure 5. Simulated (solid and dotted line) and observed (scatter plot) values of total dry biomass yield without roots (W_{tot}) for eight potato genotypes tested in Burundi: highlands (A and B) and lowlands (C and D). Genotypes are coded as follows: 388611.22 (CIP01), 388972.22 (CIP02), 390663.8 (CIP03), 395193.4 (CIP04), 395194.9 (CIP05), Ndinamagara (NDINA), Ruhanyura (RUHA) and Victoria (VICTO). DAE stands for days after emergence and *fwt* for coefficient of drought stress. Vertical bars represent the standard errors of differences between obtained means at each date of observation.

into account when sampling. However, Bacterial Wilt caused by *Ralstonia solanacearum* Yabuuchi, normally the most destructive and widespread in the sub-Sahara regions (Lemaga et al., 2001), was not observed in trials conducted in lowlands. Few wilted plants were instead observed in highlands. Observed (average across genotypes) and simulated values of shoots dry weights at final harvest time were 1.1 and 1.7 t.ha^{-1}, respectively. In lowlands, those yields rose to 2.3 and 3.5 t.ha^{-1}, respectively.

Since they had produced high tuber and shoots weights, NDINA and CIP05 took consequently the lead in total biomass productivity (excluding roots) in highlands (Figure 5A and B). In lowlands, fast growth of total plant biomass was found on clone CIP01 starting from 27 DAE mainly for trials conducted in 2006 (Figure 5C). For the rest of genotypes, this growth in lowland was delayed especially for CIP03, RUHA and CIP05 ...whose total biomass required up to two months after planting increasing substantially. However, for the last clone cited, the delay in growth was compensated by an increased growth rate from 39 DAE up. In the locations with low

temperatures (Gisozi and Ryansoro), the HI at final harvest, averaged across all genotypes, was 0.83 while the simulation program gave 0.78. However, those observed averaged HI values decreased to 0.53 and 0.34, respectively in lowlands.

The analysis of results produced by experimentation and simulation shows similarities between the two approaches assuming that there was no drought stress in lowlands (fwt = 1). Indeed, the two techniques showed that tuber yield decreases from highlands to lowlands at roughly similar rates: 64.2% in field experiments and 73.5% in simulations. The same trend occurred for HI with a rate of 36.1 and 56.1%, respectively. This was expected because the dry shoot yield was more than doubled- an increase of 116.6% in field data and 106.9% by simulation - from highlands to lowlands at final harvest time. When water stress (with fwt = 0.75) was introduced in the model prior to simulation for lowlands, simulated parameters changed as follows: dry tuber yield decreased by 21% (from 3.8 to 3.0 t.ha-1) and dry shoot yield by 37.6% (from 3.5 to 2.2 t.ha^{-1}).Unlike for biomass productivity, HI increased instead by 14.8% (from 0.341

to 0.4) for reasons discussed hereafter.

DISCUSSION

There is a balance between assimilates allocated to stems and leaves at juvenile stages but their proportion in total biomass is gradually decreasing while the proportion in tubers is increasing until final harvest when almost all assimilates are allocated to tubers (Condori, 2010; Kooman and Haverkort, 1995a). This was also confirmed by our results obtained in highlands and lowlands, except for NDINA and RUHA whose decrease in the proportion of dry matter allocated to stems over time was not evident in lowlands. This is an indication of poor adaptation of these varieties to warm climates because it has been shown that when temperature exceeds 23°C, dry matter for a non-heat tolerant genotype is allocated to the foliage at the cost of the tuber growth (Haverkort and Harris, 1987). The high tuber yielding ability of NDINA and CIP05 in highlands (cooler temperature compared to lowlands) may be explained by their long duration of development since it has been reported that the total growth and tuber dry matter production of a potato variety are related to the duration of its growth cycle (Kooman et al., 1996).

The potato model we used fitted well to data collected from field experiments (means across cultivars) even if some exceptions were sometimes observed and simulations were not run by cultivar or clone separately. Indeed, we used the model as a common reference without attempt to change or introduce new clone or variety characters. However, it is interesting to find out that when we draw our attention to the observed means per genotype and not on overall mean across varieties, some discrepancies appear. On graphs these means per genotype were differently scattered (above or below the simulated yield) according to variety (or clone) and environment, both over and underestimation being found. These differences between potato genotypes in response to high temperatures have been reported in literature (Wolf et al., 1990). In highlands, they were mostly no significant differences between simulated yields and the yields obtained from best genotypes (according to standard errors of differences between means) and this was already so in early stages of tuber bulking. However, in stages approaching final harvest, significant deviations with overestimation of prediction were found. The overestimation could come from the model itself, but also external factors such as diseases- late blight on CIP03 and CIP04, and early blight for all genotypes with varying severity- and pests, suboptimal fertilization, soil nature, etc., might explain these deviations. In lowlands, the model fitted well observations except that CIP01 exceeded significantly the simulated level (underestimation of the model) at beginning of tuber bulking in 2006. This means that a given genotype could be overestimated in an environment but underestimated in another one. This

variability between genotypes behaviour in contrasting environments makes possible the selection (or identification) of material adapted to specific conditions such as those found in the lowlands. Lowlands are characterized, in comparison to highlands, by their higher temperatures (up to 8°C of increase) but other factors may also play a role. This material adapted to lowlands has the potential to be of great use in cooler areas in the near future due to global warming. According to the fourth assessment report of the intergovernmental panel on the climate change, some varieties/species will not survive in the increase of temperature especially in Africa if they are not heat tolerant (IPCC, 2007).

In lowlands, simulation integrating drought stress enabled to quantify roughly the difference between a potential yield (limited by light and temperature) and an attainable yield taking into account also water and nutrients limitations. Tuber yield is known to be water dependent and the simulation showed that a moderate drought stress generated automatically a decrease in tuber yield. For that reason, lower yields obtained in lowlands could also be partially explained by lack of soil moisture in a region where evapotranspiration is expected to be higher than in the rest of the country. Our simulation of drought stress expressed an increase in HI as already reported in the reality under certain circumstances (Jefferies, 1992, 1995) but in most cases the opposite occurred (Deblonde et al., 1999; Jefferies, 1993). The conflicting evidence of effects of drought on partitioning of assimilate to tubers is already reported in literature (Jefferies, 1995). For example, when drought stress occurs after tubers have been initiated, the partitioning of assimilates to tubers is promoted and maturity advanced (Jefferies, 1995). Unfortunately, our field plots were irrigated and we do not have field data on droughted plants to compare with the simulation.

Nevertheless, the HI observed in lowland were lower than in highland due to a stronger negative effect of temperature than the possible positive effect of a moderate lack of water. Results presented above from field observations and simulation show also that high temperatures decrease tuber yield and HI but the shoots weight at final harvest increases regardless the genotypes used. This confirms results found elsewhere in the world (Marinus and Bodlaender, 1975; van Keulen and Stol, 1995a; Wolf et al., 1990) and in Burundi (in preparation).

Conclusion

The LINTUL model version used in this study appeared to be useful to foresee the behaviour of the potato crop in different regions (highland and lowland) of Burundi. Indeed, findings obtained from fields' observations were confirmed by simulation, the potato crop (regardless the type of genotype) being found to be more performing in highlands than in lowlands both in field observations and

simulation. The field results (observations) showed that NDINA, VICTO, CIP02, CIP04 and CIP05 were high yielding in highlands while CIP01, CIP03, CIP04, CIP05 and VICTO appeared to be adaptable to lowlands of Burundi. In addition to their adaptability to lowlands, these genotypes selected for lowlands could be of great use in mitigating the adverse effects of global warning in traditional potato areas in Burundi or elsewhere. The simulation model showed that potential yields in lowlands could be lowered further to lower attainable yields if water supply is not managed properly. Moreover, diseases such as late blight in highlands and Fusarium wilt in lowlands while early blight prevails everywhere can drop expected yields especially when genotypes grown are less tolerant.

The model applied in this study was found to be realistic in the local conditions mainly in predicting behaviour of potato in a given environment meteorologically defined. However, further work is required in order to calibrate the model for each given genotype by including some key parameters (genetic coefficients) such as time to the tuber initiation and potential (maximum) tuber growth rate.

ACKNOWLEDGEMENT

REFERENCES

Anonymous (1996). Dimethoate [Online]. Available by EXTOXNET http://extoxnet.orst.edu/pips/dimethoa.htm (posted June 1996; verified 24 April 2008).

Anonymous (1998). Dithane* M-45 [Online]. Available by Dow AgroSciences LLC http://www.dowagro.com/PublishedLiterature/dh_0042/0901b803800 42558.pdf?filepath=ca/pdfs/noreg/010-20021.pdf&fromPage=GetDoc (posted 3 February 1998; verified 24 April 2008).

Anonymous (2007). Ridomil Gold MZ 68WP [Online]. Available by Syngeta Crop Protection Canada, Inc. http://pr-rp.pmra-arla.gc.ca/PR_SOL/pr_web.ve1?p_ukid=4434 (posted 7 September 2007; verified 24 April 2008).

CIP (2011). Catalogue of the Potato varieties and Advanced clones 2011. Germplasm Enhancement and Crop Improvement and Research Informatics Unit. International Potato Center.

Condori B, Hijmans R, Quiroz R, Ledent JF (2010). Quantifying the expression of potato genetic diversity in the high Andes through growth analysis and modeling. Field Crops Res. 119(1):135-144.

Deblonde PMK, Haverkort AJ, Ledent JF (1999). Responses of early and late potato cultivars to moderate drought conditions: agronomic parameters and carbon isotope discrimination. Eur. J. Agron. 11:91-105.

Driessen PM (1986). The water balance of the soil. In: van Keulen, H. and Wolf, J. (Eds.), Modelling of Agricultural production: Weather,

Soils and Crops, Simulation Monographs. Pudoc, Wageningen pp. 76–116.

FAO (1984a). Agroclimatological data for Africa, Vol2. Countries south of the equator. FAO Plant Production and Protection Series 22. FAO, Rome.

FAO (1984b). Agroclimatological data for Africa, Vol2. Countries south of the equator. FAO, Rome.

Harahagazwe D (2003). Contribution to the participatory evaluation of nine potato genotypes for their performance in Buyengero commune: an approach in experimentation in Burundi. MSc thesis, Fac. Univ. Sci. Agron., Gembloux, Belgium.

Harahagazwe D (2006). New Potato Catalogue of Potato varieties in Burundi. Third Edition. National Agricultural Research Institute of Burundi, Bujumbura. 25 p.

Haverkort AJ, Harris PM (1987). A model for potato growth and yield under tropical highland conditions. Agric. For. Meteorol. 39:271-282.

Haverkort AJ, MacKerron DKL (1995). Potato Ecology and Modelling of Crops under Conditions Limiting Growth. Kluwer Academic Publishers, Dordrecht.

IPCC (2007). Climate Change. Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.

Jefferies R (1992). Effects of drought on chlorophyll fluorescence in potato (Solanum tuberosum L.). II. Relations between plant growth and measurements of fluorescence. Potato Res. 35:35-40.

Jefferies RA (1993). Cultivar Responses to Water Stress in Potato: Effects of Shoot and Roots. New Phytol. 123:491-498.

Jefferies RA (1995). Physiology of crop response to drought. In: Haverkort A. J., D. MacKerron, K. L. (Eds.), Potato ecology and Modelling of Crops under Conditions Limiting Growth. Kluwer Academic Publishers, the Netherlands, pp. 61-74.

Kabat P, Marshall B, van den Broek BJ, Vos J, van Keulen H (1995). Modelling and Parameterization of the Soil-Plant-Atmosphere System. A Comparison of Potato Growth Models. Wageningen Pers, Wageningen.

Kooman PL (1995). Yielding ability of potato crops as influenced by temperature and daylength. PhD thesis. Wageningen Agricultural University, Wageningen.

Kooman PL, Haverkort AJ (1995a). Modelling development and growth of the potato crop influenced by temperature and daylength: LINTUL-POTATO. In: Haverkort, A. J., MacKerron, D. K. L. (Eds.), Ecology and Modelling of Potato Crops Under Conditions Limiting Growth. Kluwer Academic Publishers, Dordrecht pp. 41-60.

Kooman PL, Spitters CJT (1995b). Coherent set of models to simulate potato growth. In: Kabat, P. Marshall, B., van den Broek, B.J., Vos, J., van Keulen, H. (Eds.), Modelling and parameterization of the Soil-Plant-Atmosphere System. A Comparison of Potato Growth Models. Wageningen Pers, Wageningen pp. 253-273.

Kooman PL, Fahem M, Tegera P, Haverkort AJ (1996). Effects of climate on different potato genotypes 2. Dry matter allocation and duration of the growth cycle. Eur. J. Agron. 5:207-217.

Lemaga B, Siriri D, Ebanyat P (2001). Effect of Soil Amendments on Bacterial Wilt Incidence and Yield of Potatoes in Southwestern Uganda. Afr. Crop Sci. J. 9:267-278.

Low JW (1997). Potato in Southwest Uganda: Threats to sustainable production. Afr. Crop Sci. J. 5:395-412.

Marinus J, Bodlaender KBA (1975). Response of some potato varieties to temperature. Potato Res. 18:189-204.

Monteith JL (1977). Climate and the Efficiency of Crop Production in Britain [and Discussion]. Philosophical Transactions of the Royal Society of London. Series B, Biol. Sci. 281:277-294.

Spitters CJT, Schapendonk AHCM (1990). Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. Plant Soil 123:193-203.

van Ittersum MK, Leffelaar PA, van Keulen H, Kropff MJ, Bastiaans L, Goudriaan J (2003). On approaches and applications of the Wageningen crop models. Eur. J. Agron. 18:201-234.

van Keulen H, Stol W (1995a). Agro-ecological zonation for potato production. In: MacKerron, D. K. L. (Ed.), Potato Ecology and Modelling of Crops under Conditions Limiting Growth, Vol. 3. Kluwer Academic Publishers, Dordrecht pp. 357-372.

Van Keulen H, Stol W (1995b). Agro-ecological zonation for potato

production. In: Haverkort A. J., MacKerron D. K. L. (Eds.), Potato ecology and modelling of crops under conditions limiting growth. Kluwer Academic Publishers, Dordrecht. pp. 357-371.

Wolf S, Marani A, Rudich J (1990). Effects of Temperature and Photoperiod on Assimilate Partitioning in Potato Plants. Ann. Bot. 66:513-520.