Kor. J. Hort. Sci. Technol. 31(1):103-109, 2013 DOI http://dx.doi.org/10.7235/hort.2013.12073

Development of Calculating System of Solids Level to Harvest High Solids Potato (*Solanum tuberosum* L.)

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Abstract. Estimating the high tuber solids needs a simulation system on potato growth, and its development should be obtained by using agricultural elements which analyze the relationship between crop growth and agricultural factors. An accurate simulation to predict solids level against climatic change employs a calculation of in vivo energy consumption and bias for growth and induction shape in a slight environmental adaptation. So, to calculate in vivo energy consumption, this study took a concept of estimate of the amount of basal metabolism in each tuber. In the validation experiments, the results of measuring solid accumulation of potatoes harvested at dates suggested by simulation agreed with the actual measured values in each regional field during the growth period of years from 2006 till 2010. The mean values of tuber solids level and inter-annual level variation in validation experiments were predicted well by the simulation model. And also, the results of validation experiments represent that concentration of tuber solids were due mainly to the duration of sunshine, above 190 hours per a month, and the cumulative amount of radiation, above 2,200 MJ·m^{-2}, of the effective growth period.

***Additional key words*:** climatic change, energy consumption, model, simulation, tuber

Introduction

Potato (*Solanum tuberosum* L.) is an important vegetable crop in Korea and is sold for fresh market and processing. It is a cool season crop and in Korea is generally grown through the months of spring and harvested in early summer. It is an intensively managed crop that requires large amounts of nutrients and water. And its yields are dependent on variety, planting date, weather conditions, production practices and harvest date.

Studies on simulation of crop growth processes began in 1960s along with the application in ecology of system analysis methodology and computer technology. Developments of the application in potato research to use more and more sophisticated simulations to evaluate complex situations that cannot be analyzed directly with other means except agricultural factors (Mazaheri et al., 2005; Spitters, 1990; Stastana and Dufkova, 2008). Their purposes were to provide information on crop development stage, irrigation timing and amount, nitrogen fertilizer requirements and timing, and expected time to harvest (NICS, 2005).

To simulate solids level in growth phase is coupled with comprehensive crop phenology in response to environmental factors especially related atmospheric processes such as temperature and humidity. The progress of dynamic crop growth models needs considerably improved analytic solution of problems in crop sciences. The simulation model, in this study, is valid outside conditions for which it was originally calibrated due to results of measuring solid accumulation of potato harvested. So this study not only can enhance the understanding of the relationships between the crop and surrounding environmental factors, but also can promote the field potato production with high tuber solids.

Materials and Methods

Required input data for simulation modeling calibration and evaluation were collected at 8 experimental fields in Korea: Inje, Jeongseon, Yeoju, Dangjin, Gumi, Gimje, Namji, and Boseong. The calibration and evaluation process proceed on followed subsequent stages as data collection of the experimental data, calibration of simulating results, assessment

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※ Received 9 April 2012; Revised 12 September 2012; Accepted 19 September 2012. This study was supported by MIFAFF/iPET (Ministry for Food, Agriculture, Forestry and Fisheries/Institute of Planning & Evaluation for Technology) of Korea.

of the possibilities and limitations. Various types of input data including the weather data set and field management data were obtained from field measurement and analysis as the follows.

Mathematical Model Description

To calculate the accumulation and partitioning of biomass and the phenological development of a potato crop, a mathematical model is described by environmental factors such as solar radiation quantity, temperature, photon quantity, water stress and loss, and wind etc. The schematic model is shown in Fig. 1 on potato growth and its development should be obtained by using agricultural elements. The model has contemplated the timing, rate and duration of tuber initiation. It, in the eq. 1, is inducted from crop emergence to maturity and is carried out in time steps of dt. The eq. 1 employs both potato growth under optimal nutrient and water supply, taking into account the climatic conditions, and growth without irrigation, also considering the amount of available soil water. Maintenance requirements of a potato crop, calculated as a function of crop weight and chemical composition, are subtracted from daily gross assimilation. The remaining assimilates are allocated to the different crop organs. All plant entities, in the Fig. 1, are expressed on a per plant basis. The eq. 1 contains the state variables metabolism and assimilate pool, leaf, stem, root, and tuber for organ populations. The dry matter ($\triangle DM$) is built around the following basic growth equation:

$$\triangle DM = \int_{t}^{m} f(x)\,dt \qquad (1)$$

$$f(x) = \frac{\triangle W}{\triangle t} = (Dp/(Dv \cdot \triangle LA)) \cdot \triangle A - \triangle EL,\ f(x) \geq 0 \qquad (2)$$

$\triangle DM$: daily dry matter increase [g·d^{-1}/plant]
Dp : density of plants
Dv : density of vines
$\triangle LA$: specific leaf area [m^{2}·g^{-1}]
$\triangle EL$: energy loss during growth stage [g·MJ^{-1}]

The amount of photosynthesis ($\triangle A$) follows prior works (Biemond and Vos, 1992; Hajirezaei et al., 2000; Katny et al., 2005) as given in eq. 3. The interception of radiation follows a De Beer's law function (eq. 4). *PAI* stands for plant area index and *GR* is the total daily incoming global radiation.

$$\triangle A = IR \cdot BM \cdot f_1(QP) \cdot f_2(TP) \cdot f_3(H_2O/g) \cdot f_4(WS) \cdot f_5(CO_2) \qquad (3)$$

$$IR = (1 - e^{0.5 \cdot PAI}) \cdot GR \cdot 0.01 \qquad (4)$$

IR : intercepted radiation [MJ·m^{-2}·d^{-1}]
BM : biomass of potential growth rate [g·MJ^{-1}·d^{-1}]
QP : quality of photo (RUE) [g·MJ^{-1} PAR]
TP : temperature potential [℃·1^{-100}]

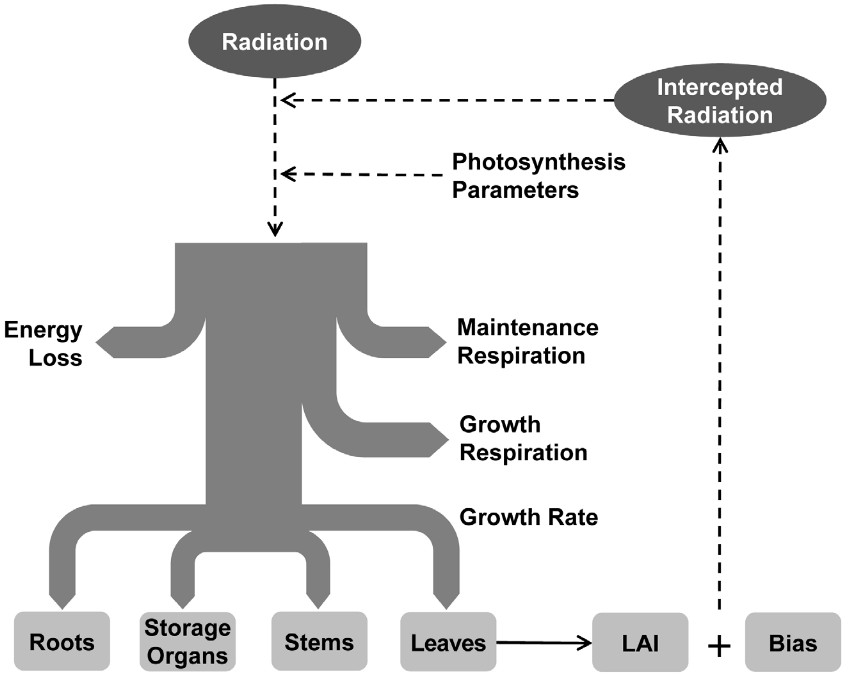

Fig. 1. Schematic of the calculation of potato growth model based on works by Kooman (1995), Spitters (1990), and Jung and Suh (2010).

WS : water stress factor [%·1^{-100}]
GR : total daily incoming global radiation [MJ·m^{-2}·d^{-1}]

$$PAI = LAI + (DMs \cdot DMc) \cdot \triangle LA / Dp \qquad (5)$$

PAI : plant area index
LAI : leaf area index
DMs : dry matter of stems [g/plant]
DMc : dry matter of conversion factor

The eq. 5 for computing plant area index takes both concepts a dry matter of stems and a dry matter of conversion factor. To consider differing productivities of leaves of a different age and leaf senescence, the leaf biomass of a day is no longer influenced by a conversion factor in this concept.

Energy Loss Description

The eq. 6 describes the energy loss in the growth of a potato crop. It is a matter of primary consideration for tuber initiation which is an instantaneous event, like emergence, rather than a distinct growth stage. The growth and partitioning before and just after emergence is modeled differently than during later crop growth.

$$\triangle EL = Es + Ei \qquad (6)$$

$$Es = \Sigma_i (BMo_i \cdot \Delta t),\ \Delta t = (\Sigma_i BMo_{ij})/t_i \qquad (7a)$$

$$Ei = \Sigma_j \Sigma_{i \in I_i} BMo_{ij} (\alpha dt_{ji} + \beta dt_{ij}) \qquad (7b)$$

$$\max_{i \in I_i} \left(\frac{BMo_{ij}}{t_{ij}} + dt_{ji} + dt_{ij} \right) \leq D_j,\ \forall j = 1, 2, \cdots, J$$
$$\Sigma_i BMo_{ij} = r_j,\ \forall j = 1, 2, \cdots, J$$
$$\Sigma_i t_{ij} = t_i,\ \forall i = 1, 2, \cdots, N$$

over $BMo_{ij} \geq 0,\ t_i \geq 0,\ t_{ij} \geq 0$
where: Es : energy of shape [g·MJ^{-1}]
Ei : energy of induction [g·MJ^{-1}]
BMo : biomass of organs growth rate [g·MJ^{-1}·d^{-1}]
dt : delay time for metabolism
D : total delay time during growth stage
t : time consuming for metabolism

As long as the energy of induction is smaller than D_j the contribution energy loss is taken from the tuber and allocated to the different plant organs by applying the same inducting shape as before harvesting.

Data Acquisition for Simulation

For application of the model, data that specify potato growth, phenological development and assimilate allocation are required. In shown Tables 1 and 2, regarding factors consisting of site specific, environmental specific and crop specific parameters are stored in files, which also contain the eventually measured data series. Daily temperatures, humidity, precipitation, wind, and solar radiation are required for the simulation to calculate assimilation levels of tuber solids. To calculate the level of tuber solids, historical and generated sets of daily weather data of experimental fields over a period of last 5 years (2006-2010) were used. The using tools for collecting weather data are thermometers (TX-500 and SK-1250), a sunshine recorder (Jordan Sunshine Recorder), a weather observatory system (WXT510), and Karl Fischer method(KP VIII [26] Water Determination) to measuring solids concentration.

Results

Simulation was calibrated and tested against the results from a number of validation experiments and modeling trials in 8 experimental fields in Inje, Jeongseon, Yeoju, Dangjin, Gumi, Gimje, Namji, and Boseong. For analysis of the possible

Table 1. Regarding factors of potato growth and development process on agricultural environment.

	Growth		Development	
	Biomass	Straight Growth	Inducted Development	Phenological Development
Principal environmental factor	Solar radiation Water	Temperature Water	Temperature Photoperiod	Temperature
Variation on genotype	High	Low	High	Low
Sensitivity to plant water deficit	Stomata and wilting point	Low: tuber enlargement	Delay in vegetative stage	Damage to vascular system
Sensitivity to temperature degree days	Tuber formation	Vegetative stage	High	High
Sensitivity to nitrogen content	Moderate: high solid High: low solid	High	Low	Luxuriant growth

Table 2. Mean value of agricultural environment factors in each regional field on farming days for the last 5 years (2006-2010).

Field	Environmental Factor	Month									Cropping Type
		1	2	3	4	5	6	7	8	9	
Inje	Mean Temp. (℃)				10.5	15.8	20.1	22.9	23.7	18.8	Spring
	RH (%)				56.3	63.2	69.4	79.1	77.3	76.3	
	Precipitation (mm)				57.3	103.9	146.1	427.3	240.0	150.5	
	Wind ($m\cdot s^{-1}$)				2.5	2.2	2.1	1.9	2.0	1.9	
	Duration of Sunshine (hour)				174.0	197.0	185.3	117.5	159.0	143.0	
	Soil Temp. (℃)				10.6	17.6	23.4	25.3	26.4	21.0	
Jeongseon	Mean Temp. (℃)				11.3	16.6	20.9	23.5	24.3	19.4	Spring
	RH (%)				53.3	60.8	67.9	78.6	75.8	74.3	
	Precipitation (mm)				48.2	83.3	125.6	271.9	265.2	165.5	
	Wind ($m\cdot s^{-1}$)				2.2	1.8	1.6	1.3	1.4	1.5	
	Duration of Sunshine (hour)				187.2	213.7	180.0	103.9	147.7	137.6	
	Soil Temp. (℃)				13.6	20.8	25.4	26.6	28.2	23.0	
Yeoju	Mean Temp. (℃)			5.1	11.9	17.4	21.7	24.1			Spring
	RH (%)			64.2	59.0	64.4	71.9	81.6			
	Precipitation (mm)			56.3	56.1	94.2	136.8	455.2			
	Wind ($m\cdot s^{-1}$)			1.8	1.8	1.5	1.3	1.1			
	Duration of Sunshine (hour)			196.0	194.9	218.4	178.7	112.7			
	Soil Temp. (℃)			5.6	13.1	19.2	25.3	25.9			
Dangjin	Mean Temp. (℃)			4.6	10.7	16.1	20.8	25.9			Spring
	RH (%)			66.9	66.7	70.9	76.8	85.5			
	Precipitation (mm)			48.2	56.7	96.4	152.6	365.1			
	Wind ($m\cdot s^{-1}$)			3.2	3.4	3.0	2.8	2.7			
	Duration of Sunshine (hour)			202.2	199.2	226.7	158.1	93.7			
	Soil Temp. (℃)			6.6	12.8	19.0	23.6	25.5			
Gumi	Mean Temp. (℃)			6.1	12.7	18.0	21.8	24.0			Spring
	RH (%)			54.8	54.0	60.3	71.4	82.1			
	Precipitation (mm)			37.6	39.8	58.9	109.8	203.7			
	Wind ($m\cdot s^{-1}$)			2.7	2.3	1.8	1.3	1.1			
	Duration of Sunshine (hour)			203.0	197.8	222.9	174.9	111.1			
	Soil Temp. (℃)			7.8	14.3	21.4	25.6	26.6			
Gimje	Mean Temp. (℃)			6.6	13.0	18.3	22.8	25.6			Spring
	RH (%)			59.8	57.5	61.8	68.9	77.6			
	Precipitation (mm)			54.4	45.0	90.1	153.7	348.3			
	Wind ($m\cdot s^{-1}$)			2.3	2.4	2.2	2.0	2.1			
	Duration of Sunshine (hour)			191.9	193.9	213.7	157.6	98.1			
	Soil Temp. (℃)			8.5	15.2	21.5	25.4	23.7			
Namji	Mean Temp. (℃)		2.2	7.0	12.8	17.6	21.7				Early Spring
	RH (%)		50.9	54.0	56.3	60.3	66.4				
	Precipitation (mm)		23.3	55.8	64.5	124.3	142.5				
	Wind ($m\cdot s^{-1}$)		1.5	1.6	1.8	1.6	1.5				
	Duration of Sunshine (hour)		183.6	203.5	197.1	206.2	143.5				
	Soil Temp. (℃)		2.8	7.6	14.6	20.7	24.6				
Boseong	Mean Temp. (℃)	1.3	2.2	6.3	11.8	16.9	21.0				Early Spring
	RH (%)	66.4	62.7	63.9	66.4	70.9	77.6				
	Precipitation (mm)	22.0	38.0	75.8	89.1	186.7	197.5				
	Wind ($m\cdot s^{-1}$)	2.7	3.1	2.8	2.5	2.3	2.1				
	Duration of Sunshine (hour)	150.2	180.0	204.4	202.5	225.8	144.1				
	Soil Temp. (℃)	1.5	3.0	8.1	14.5	20.7	24.4				

Table 3. Amount of Radiation (MJ·m^{-2}) and RUE (Radiation Use Efficiency; subject to 400-700 nm; Sinclair and Muchow, 1999) in each regional field on farming days for the last 2 years (2009-2010).

Field	Environmental Factor	Month 1	2	3	4	5	6	7	8	9	Variety
Inje	Amount of Radiation				489	577	553	426	580	427	Atlantic
	RUE				1.88	1.88	1.89	1.87	1.88	1.87	
Jeongseon	Amount of Radiation				495	592	541	458	563	432	Atlantic
	RUE				1.88	1.89	1.89	1.87	1.88	1.87	
Yeoju	Amount of Radiation			384	496	579	505	473			Atlantic
	RUE			1.86	1.87	1.88	1.88	1.88			
Dangjin	Amount of Radiation			387	507	581	469	491			Atlantic
	RUE			1.87	1.88	1.88	1.87	1.88			
Gumi	Amount of Radiation			412	539	609	518	517			Dubaek
	RUE			1.91	1.90	1.89	1.90	1.90			
Gimje	Amount of Radiation			411	548	598	457	546			Atlantic
	RUE			1.87	1.88	1.88	1.88	1.88			
Namji	Amount of Radiation		341	415	572	601	433				Atlantic
	RUE		1.87	1.87	1.88	1.88	1.88				
Boseong	Amount of Radiation	311	339	394	541	597	431				Atlantic
	RUE	1.87	1.87	1.88	1.88	1.88	1.88				

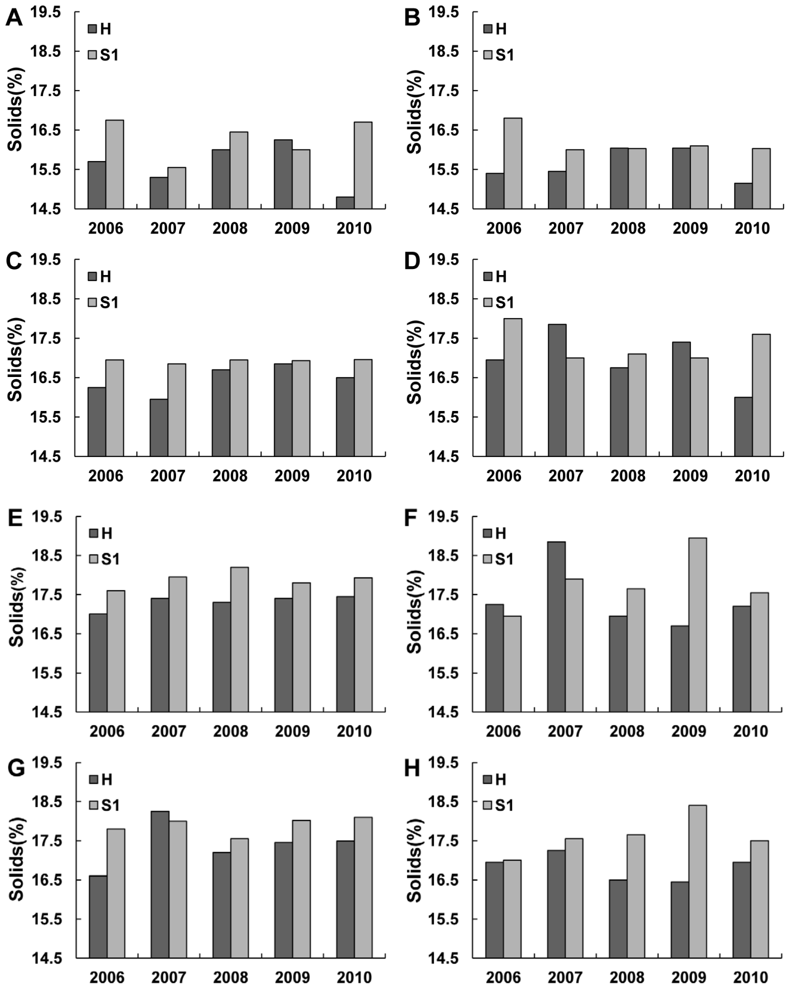

Fig. 2. Comparison with tuber solids between harvested levels (H) and simulated levels (S; to the exclusion of $\triangle EL$ and bias) in each regional fields (A: Inje, B: Jeongseon, C: Yeoju, D: Dangjin, E: Gumi, F: Gimje, G: Namji, H: Boseong) for evaluation of in vivo energy loss approaches.

Table 4. The comparison with tuber solids concentrates for harvesting potato of both actual date with non-simulation and suggested date with simulation in each regional field.

Field	Year										Variety
	2006		2007		2008		2009		2010		
	H^{z}	S^{y}	H	S	H	S	H	S	H	S	
Inje	15.51	15.70*	15.20	15.32*	16.04	16.03^{ns}	15.93	16.24*	15.37	15.90**	Atlantic
Jeongseon	15.36	15.37^{ns}	15.37	15.44*	16.02	16.06^{ns}	15.88	16.05*	15.04	15.14*	Atlantic
Yeoju	15.93	16.24*	16.04	16.02*	16.24	16.78**	16.40	16.95**	16.14	16.48*	Atlantic
Dangjin	16.41	17.02**	17.79	17.81*	16.61	16.82*	17.53	17.45*	16.05	16.03^{ns}	Atlantic
Gumi	17.31	17.05*	17.24	17.37*	16.94	17.29*	17.14	17.35*	17.06	17.40*	Dubaek
Gimje	16.74	17.25**	18.75	18.92*	16.74	17.02*	16.63	16.75*	17.29	17.24*	Atlantic
Namji	16.36	16.76*	17.93	18.25*	16.79	17.29*	17.41	17.54*	17.15	17.56*	Atlantic
Boseong	16.80	17.03*	17.21	17.35*	16.46	16.53*	15.77	16.47**	16.78	17.04*	Atlantic

^{z}Days to harvest, ^{y}Simulated days to harvest, ^{ns}Non significant, $*p < 0.05$, $**p < 0.01$.

effects of climate change, tuber production of calculated high tuber solids to separately changed values of weather variables was determined. The collection of weather data during the growth period of the last 5 years, 2006-2010, was carried out (Table 2). A cropping type was spring in experimental fields. In Boseong and Namji, there were a bit of fast cropping season at the early spring in shown Table 2. The early spring cropping type in Boseong and Namji is probably due to high soil temperature levels in winter which was the case in Boseong and the resulting capillary rise, which were not taken into account in these analyses.

Tuber production was considerably increased with the amount of radiation of ≥ 500 (Table 3 and Fig. 2) when no calculation of *in vivo* energy loss in amount of photosynthesis (△A) was applied (in eq. 2). The radiation use efficiency (RUE; Sinclair and Muchow, 1999) to a potato crop was rather limited, owing to its relatively intercepted radiation and photo quality (Table 3). It indicates that the simulated assimilation level can be attained on the concepts of using metabolic energy for inducted and phonological development. However, unknown factors resulted in a lower observed mean tuber solids level and a larger amount of solids variability on energy loss concepts than on no energy loss and in a difference between simulated measured tuber solids. Individually or in combination, the unknown factors seem to be a bias influenced by the agricultural environmental variables temperature, humidity, wind, and photoperiod in a day (Santhosh Mithra and Somasundaram, 2008; Sinclair and Muchow, 1999).

The results of measuring solids, for different varieties (Atlantic and Dubaek) during the last 5 years in shown Table 4, represent the harvesting potato with simulation higher than the other from non-simulated harvesting potato, except for 2006 of Jeongseon, 2008 of Inje, 2008 of Jeongseon, and 2010 of Dangjin. The comparison with tuber solids concentrates and RUE on total biomass to different geographical positions was almost identical. Gimje, in Table 4, has high tuber solids regime of ≥ 17.0%. This resulted in a little higher soil temperature (8.5℃, 15.2℃, 21.5℃, 25.4℃, and 23.7℃ in shown Table 2) with somewhat lower precipitation (54.4 mm, 45.0 mm, 90.1 mm, 153.7 mm, and 348.3 mm in shown Table 2) and, thus, in a higher tuber solids, but only if no unusually cold temperatures worked. Cumulative solids had a maximum close to that for the present biomass regime, which was mainly due to the duration of sunshine, above 190 hours per a month, and the cumulative amount of radiation, above 2,200 MJ·m^{-2}, of the effective growth period.

Discussion

The emphasis in a simulation systems approach is to develop targeted information for influencing the most relevant decisions in the system of interest. This concept is relevant across the wide range of scales and issues associated with cropping systems. The simulation model had limited cropping types of spring and early spring (Table 2) in the description of growth processes. Hence, the number of agricultural factors relations that needed to be tested, the number of equations that needed calibration to site-specific conditions, and the required data base of inputs were more limited than in the simulation model (Santhosh Mithra and Somasundaram, 2008). The simulated results, in Table 4, with concept of in vivo energy loss are advantageous to higher regime of tuber solids in regional-scale studies (Jung and Suh, 2010). In a more detailed calculation, the growth processes, the responses of these processes to changes in agroecological conditions, and the interactions between these responses are needed verifications in a more mechanistic way. The growth processes of potato in Fig. 1 consist of growth rate, growth respiration, maintenance respiration, and energy loss (Jung and Suh, 2010; Kooman, 1995; Spitters, 1990). The comparison of the results from the levels of tuber solids indicated the differences in their metabolism approaches and the sort of environmental conditions in which the simulated results differed and may become less reliable in except for *in vivo* energy loss (comparing with Table 4 and Fig. 2).

A major issue for all sectors of the potato industry is predicting the tuber solids level of potato crop. Results from the simulation model were compared with results from potato experiments at 8 regional fields. The average tuber solids level and the inter-annual variation in tuber solids depending on cropping conditions were predicated well by simulation model (Table 4 and Fig. 2). Data on biomass production, assimilate distribution between crop organs. A lower biomass and results also showed that average solids level and inter-annual solids level variation of the average of both varieties were almost identical to average and variation of the variety. The difference between the simulated and observed levels of tuber solids was considerable for the early spring and spring cropping production. The relationship between agricultural environment and crop growth is complicated, since a large number of climate factors, environment factors, and crop characteristics are involved. In addition, crop growth mainly appears to respond to changing conditions in a non-linear way (Nonhebel, 1994). This indicated that tuber yields on cumulative tuber solids were limited by water condition, especially in the early shoot growth stage, and also a few water-stressed yields from simulation were sometimes too high in Boseong and Gimje.

The sensitivity of computing tuber solids to systematic changes in agricultural climate was calculated with the simulation model for high tuber solids. These climate effects that were largely determined by in vivo energy loss approaches, were already discussed in the agricultural factors (Jung and Suh, 2010; Santhosh Mithra and Somasundaram, 2008; Sinclair and Muchow, 1999). No water stressed tuber production from the simulation model considerably increased with increases in both solar radiation and atmospheric condition such as CO_2 concentration and had its optimum at present temperatures in each regional fields (Mazaheri et al., 2005; Nonhebel, 1996). The simulation results were the lower solids levels for present conditions, the weaker and stronger increases with increasing radiation and atmospheric condition, respectively (Tables 2 and 3). In water stress condition, production from simulation model had a slightly lower temperature optimum than present temperatures, considerably increased with increases in amount of precipitation, atmospheric condition, and vapor pressure, and decreased with an increase in wind speed (Mazaheri et al., 2005; Stastana and Dufkova, 2008). These results correspond well with the sensitivity of tuber solids to temperature in simulation model, which calculated maximum level of tuber solids at the present temperatures.

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