Design and implementation of maize (Zea mays L.) growth simulation model for Northwest region in China

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Design and implementation of maize (*Zea mays* L.) growth simulation model for Northwest region in China

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Abstract: *A temperature driven maize growth simulation model, NWMSim, was developed by analyzing the quantitative growth of maize on a daily time step and emphasizing the yield prediction with special focus on Northwest region in China. It simulates daily growth and development, total accumulation of dry matter and final grain yield for a single crop season. The simulation runs through seven major phenological stages within the crop cycle including sowing date, germination and emergence, three-leaf unfolding, jointing, booting, spinning and harvesting. Primarily the model development was based on the Growing Degree Days (GDD). The model validation was done using five years field observations (2005, 2006, 2007, 2009 and 2011) collected from Yangling in Northwest region in China. Simulated and observed data were statistically analyzed and compared. The grain yield was slightly over estimated for three cropping cycles (2006, 2007 and 2011) however the coefficient of determination (R2=0.94) has shown a positive agreement. The obtained all results have shown an accurate agreement between simulated and observed values for both development and growth variables. Based on the results and the comparisons of simulated and observed values, it can be used as a prediction tool in maize cultivation and also an economic management tool in economic planning at regional level.*
Keywords: *Maize, maize growth models, Growing Degree Days, phenological stages.*

Riassunto: *Un modello di simulazione della crescita di mais basato sulle temperature, NWMSim, è stato sviluppato analizzando la crescita quantitativa giornaliera del mais e mettendo in evidenza la previsione di resa, avendo come focus area la regione nord-occidentale della Cina. Tale modello simula la crescita e lo sviluppo giornaliero, la sostanza secca totale cumulata e la resa in granella. La simulazione è stata fatta sulla base delle sette principali fasi fenologiche del ciclo colturale: data di semina, di germinazione e di emergenza, tre foglie dispiegate, allungamento degli internodi, riempimento delle cariossidi, fioritura e maturazione, raccolta. Il modello di sviluppo è basato principalmente sulla somma termica (GDD). La validazione del modello è stata fatta su cinque anni di osservazioni di campo (2005, 2006, 2007, 2009 e 2011) nella regione nord-occidentale della Cina. I dati osservati e simulati sono stati analizzati statisticamente e confrontati. La resa in granella è risultata di poco sovrastimata per tre cicli colturali (2006, 2007 e 2011), comunque il coefficiente di determinazione è risultato alto (R2=0.94). Tutti i risultati ottenuti hanno mostrato una buona corrispondenza tra i valori, simulati e osservati, di sviluppo e di crescita. Sulla base dei risultati e del confronto tra valori osservati e simulati, il modello sviluppato può essere utilizzato come strumento di previsione nella coltivazione del mais e anche come strumento di gestione economica nella pianificazione regionale.*
Parole chiave: *Mais, Modelli di crescita, Somma Termica, Fasi fenologiche.*

1. INTRODUCTION

Maize is one of the most important cereal crops in all over the world producing 872 Mt which is the largest rank in global cereal production in 2013. China has turned to be the second largest producer with 206 Mt of global maize production in 2013 (FAOSTAT, 2013). Nevertheless the demand of cereals in China still urges to increase the cereal production by at least 35% within two decades (Meng *et al.*, 2013; Zhang, 2011). Also, the greater demand for meat in China boosts the maize production in terms of production of animal feeds (Belfield and Brown 2008). In this context the disposal of advanced tools able to perform accurate yield estimation at regional level could be useful to address the choices of multiple stakeholders of agricultural sector with the aim to increase of domestic cereal productions. Therefore, the regional level accurate yield estimation of the maize has become more important and, in fact, a big challenge (Wang *et al.*, 2013; Xiong *et al.*, 2007). The accurate estimation of maize yield can be done by yield monitoring and yield simulations (Wang *et al.*, 2013; Priya and Shibasaki, 2001; Maselli *et al.*, 1992). Therefore, maize growth simulation models have become more popular replacing traditional yield monitoring methods (Wang *et al.*, 2013). The cited literature clearly show that direct involvement of crop growth models for maize

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production has been achieved a steady increment of the production during last hundred years (Ciampitti and Vyn, 2012). Numerous maize-specific growth simulation models have been developed in last few decades; CERES-Maize (Jones *et al.*, 1986), APSIM-Maize (McCown *et al.*, 1996), Hybrid-Maize (Yang *et al.*, 2004), GRAAL (Drouet and Pages, 2003), MSM (Zand-Parsa *et al.*, 2006). CERES-Maize is the frequently used and most referred model among the maize-specific growth simulation models. It considers several processes involved in crop growth and development and it was tested under a broad spectrum of agro climatic and pedological conditions (Nouna *et al.*, 2000; Liu *et al.*, 2012; Mastrorilli *et al.*, 2003 and Dejonge *et al.*, 2012). Yang *et al.* (2004) pointed out that the field experiments done in different environments using maize-specific models have revealed that the simulated maize yields are well below the maize yield potential. The reasons for that are discussed in detail in Yang *et al.,* (2004) and they have developed the Hybrid-Maize by acquiring two modeling approaches from maize-specific model such as CERES-Maize and generic models such as INTERCOM (Kropff and van Laar, 1993) and WOFOST (van Diepen *et al.*, 1989) to overcome the problems.

However, the regional yield simulation models are not well developed and documented thus the accurate crop yields cannot be estimated in regional level. Therefore a regional-specific maize model will have a greater value in yield simulation in a particular region. Major objective of this research was to design and implementation of maize growth simulation model for Northwest region in China. The proposed maize growth model, NWMSim, is a temperature driven maize growth simulation model which was developed by analyzing the quantitative growth of maize in daily basis and emphasizing the potential yield prediction with special focus on Northwest region in China.

2. MATERIALS AND METHODS

The model simulates daily growth and development, total accumulation of dry matter and final grain yield for a single crop season. The simulation runs through seven major phenological stages within the crop cycle including sowing date, germination and emergence, three-leaf unfolding, jointing, booting, spinning and harvesting. Primarily the model development was based on Growing Degree Days (GDD) and major formulas extracted from CERES-maize and Hybrid-Maize with some modifications.

2.1 Model development

2.1.1 GDD calculation

Temperature is the major driving factor of the development and growth of Maize plant (Robert *et al.*, 2000; Bassu *et al.*, 2014). The concept defined with temperature for the maize growth is called as "thermal accumulation". This can be explained as "thermal units" which are used to represent the development stages of the plant. These thermal units are called as "Growing Degree Days" (GDD) (Robert *et al.*, 2000) and the NWMSim runs through GDD on daily basis. The daily GDD was calculated as,

$$GDD = \frac{Tmax + Tmin}{2} - Tbase \quad (1)$$

where, *GDD* is Growing Degree Days (°C), *Tmax* is daily maximum air temperature (°C), *Tmin* is daily minimum air temperature (°C) and *Tbase* is base temperature (10°C). This Calculation of GDD is the first iterative procedure and these daily GDD values are accumulated until it reaches the required GDD value of a particular stage. The iteration procedure initializes at the sowing date and terminates at the harvesting stage. The model calculates the daily GDD continuously until simulation terminates. Calculations of GDD for some minimum and maximum temperatures are shown in Tab. 1.

2.1.2 Growth stages

Seven growth stages were considered from emergence to physiological maturity using leaf collar method. We proposed seven growth stages for the model because most of the scientists in Northwest China conduct their experiments for maize using seven stages including Sowing date, Germination and emergence, Three-leaf unfolding, Jointing (Tassel initiation), Booting (end of leaf

Temperature, °F		GDD
Minimum	Maximum	
44	56	3
47	56	3
54	70	12
60	76	18
65	81	23
70	86	28
74	92	30
74	98	30

Tab. 1 - GDD calculation for some minimum and maximum temperatures (Robert *et al.*, 2000).
Tab. 1 - Calcolo della somma termica (GDD) per alcune temperature minime e massime (Robert et al.*, 2000).*

growth), Spining (silking) and Harvest (effective grain filling period to maturity). Simulation is initialized at the sowing date event. In stage 2, germination mainly depends on the soil moisture content and the wilting point of the soil. If soil moisture content is greater than wilting point, germination occurs, if not, and if it gets more than 15 days without germination, germination failure was assumed. The required GDD (*ReGDD*) to reach stage 1 to stage 2 was calculated as a function of planting depth (*Pdepth*) as,

$$ReGDD = 20 + 6 \times Pdepth \tag{2}$$

where, *ReGDD* is required GDD to change stage (^{0}C) and *Pdepth* is planting depth (cm).When accumulated GDD are higher than *ReGDD* (Accumulated total GDD from sowing date > *ReGDD*), emergence occurs. In emergence (stage 2), it is assumed that same emerging characteristics are existing and there are no tillage and soil crusting effects, and leaf and stem growth starts. At the stage 3, the three-leaf unfolding level which is temperature dependent, vegetative growth occurs. Early phase of the jointing (stage 4) is mainly dependent on temperature and tassel initiation phase is sensitive to photoperiod. After jointing stage, it enters to the booting (stage 5). At this stage, growing point has changed to produce reproductive cells and total number of leaves is determined. At the end of this stage, it will achieve the maximum leaf number. Silking, pollination, grain setting and ear formation starts at the spinning (stage 6). It is assumed that pollination occurs when cumulative GDD reach to 170 after the silking. Effective grain filling and physiological maturity are considered to be occurred in the last stage. Further, increasing of leaf senescence and decreasing of leaf weight also starts in the stage 7. In this stage, stems and ears are the only active organs. Although the grain development has two phases; cell division (lag phase) and cell expansion (linear phase), NWMSim considered only linear phase. The lag phase is relatively short and difficult to include in the model.

2.1.3 Photosynthesis

The driving force of maize growth in potential level is photosynthesis (Penning *et al.*, 1989). The calculations of gross photosynthesis are based on the theories of Penning *et al.*, (1989). Photosynthetically active radiation (*PAR*) in between 400-700nm light spectrum could only be used for photosynthesis. Therefore, *PAR* was calculated as the half of daily solar radiation (*SR*) (Penning *et al.*, 1989). PAR is used to calculate the potential carbohydrate production (*PCP*) in a particular stage. According to the Jones and Kiniri (1986), the daily potential plant growth rate (*PPGR*) (g/plant) can be given by,

$$PPGR = \frac{RE \times PAR}{Pplants}\left(1 - e^{(-k \times LAI)}\right)CO_2 \tag{4}$$

where, *PPGR* is daily potential plant growth rate (g/plant), *RE* is radiation use efficiency (g MJ/m^2/d), *PAR* is photosynthetically active radiation (MJ/m^2/d), *Pplants* is plant population (no. of plants/m^2), *LAI* is leaf area index (m^2/m^2), *k* is light extinction factor and CO_2 is CO_2 modification factor. *Pplants* and *TLA* (Total leaf area per plant) were used to calculate *LAI*. Limitations to photosynthesis due to temperature effects (*RFP*) were calculated by (Jones and Kiniry, 1986),

$$RFP = 1 - 0.0025 \times [(0.25 \times Tmin + 0.75 \times Tmax) - 26]^2 \tag{5}$$

where, *RFP* is reducing factors for photosynthesis for low and high temperatures (0-1), *Tmin* and *Tmax* are daily minimum and maximum temperatures (°C). Then the potential carbohydrate production (*PCP*) was calculated by applying *RFP* to the *PPGR* as,

$$PCP = PPGR \times RFP \tag{6}$$

Where, *PCP* is potential carbohydrate production rate corrected for thermal limitation, *PPGR* is potential plant growth rate and *RFP* is the factor referring to the limitations to photosynthesis due to temperature effects.

2.1.4 Plant growth

(1) Leaf growth and senescence

Leaf expansion and increasing of number of leaves are continued until flowering. The value for the number of fully expanded leaves is initiated as 0.5 (*FXLN* = 0.5, unitless) at the beginning of the simulation process. Then the number of leaves (*NL*) was calculated using following functions of daily temperature (Jones and Kiniri, 1986; Yang *et al.*, 2013) as,

$$\begin{aligned} &\text{If } FXLN < 5,\ IV = 0.66 + 0.668 \times FXLN \\ &\text{If } FXLN \geq 5,\ IV = 1 \\ &FDLN = \mathrm{GDD}/(38.9 \times IV) \\ &FXLN = \textstyle\sum_1^n FDLN \\ &NL = FXLN + 1 \\ &n = \text{number of days in particular stage} \end{aligned} \tag{7}$$

Where, *FXLN* is fully expanded number of leaves, *IV* is an intermediate variable, *FDLN* is rate of daily emitted number of leaves, *GDD* is daily thermal accumulation from emergence to silking and *NL* is the number of leaves. Leaf weight and leaf area calculations are initiated after emergence, and both of them are mainly depend on the temperature. Leaf area calculation were done using the following equations as (Jones and Kiniri, 1986; Yang *et al.*, 2013), From emergence to tassel initiation,

$$\text{If } NL<4,\ LA = 3 \times NL \times FDLN \qquad \text{If } NL\geq 4,\ LA = 4 \times NL^2 \times FDLN \tag{8}$$

After the tassel initiation,

$$\text{If } NL<12,\ LA = 3.5 \times NL^2 \times FDLN$$

$$\text{If } 12<NL \leq (TLN-3),\ LA = 3.5 \times 170 \times FDLN \tag{9}$$

$$\text{If } NL> (TLN-3),\ LA = 3.5 \times 170 \times FDLN / (NL+5-TLN)^{0.5}$$

Total leaf area (TLA) is,

$$TLA = \sum_1^n LA \tag{10}$$

n = number of days in particular stage

where *LA* is the daily leaf area expansion rate (cm^2/plant) and *TLN* is total number of leaves . Leaf growth is terminated after silks emerge while leaf senescence (*LS*) continues until end of the life cycle of the plant. Then the *LS* was calculated using following equations as (Jones and Kiniri, 1986; Yang *et al.*, 2013), Until tassel initiation,

$$LS = GDD \times TLA/10000 \tag{11}$$

Tassel initiation to silking,

$$LS = TLA/1000 \tag{12}$$

Silking to effective grain filling,

$$LS = TLA \times (0.05 + SGDD/170^{0.5}) \tag{13}$$

At maturity

$$LS = TLA \times (0.1 + 0.8(SGDD/TGDD)^3) \tag{14}$$

Where *LS* is leaf senescence (cm^2/plant), *GDD* is cumulative *GDD* at tassel initiation, *TLA* is total leaf area, *SGDD* is cumulative *GDD* at effective grain filling and *TGDD* represents the total growing degree days accumulated between the spinning and the maturity stages.

Then the leaf weight (*LW*) was calculated as,
Up to 12 number of leaves,

$$LW = (LA/250)^{1.25} \tag{15}$$

After 12 number of leaves,

$$LW = 0.00116 \times LA \times TLA^{0.25} \tag{16}$$

Cumulative leaf weight (CLW) is calculated as,

$$CLW = \sum_1^n LW \tag{17}$$

n= number of days in particular stage

(2) Stem growth

Stem growth was calculated using different equations adapted from Jones and Kiniry (1986) and Yang *et al.*, (2013) at different stages. After stage 6, stems start to supply carbon and nitrogen for development of grain instead of stem growth.

Up to the stage 6,

$$\text{If } NL\leq (TLN-3),\ SG = LW \times 0.0182\,(NL-LNE)^2 \tag{18}$$

$$\text{IF } NL> (TLN-3),\ SG = 10.85 \times FDLN \tag{19}$$

After the stage 6,

$$SG = 0.4 \times EG \tag{20}$$

Where *SG* is stem growth rate (g/plant/day), *LW* is rate of leaf weight (g/plant/day), *NL* is number of leaves, *LNE* is number of leaves at the end of jointing, *FDLN* is fraction of daily leaf number, *EG* is daily ear growth rate (g/ear/day).

(3) Ear growth

Ear growth starts after silking and terminates at the starting of effective grain filling. The requirement of the carbon and nitrogen of grain growth is supplied by leaf and stems. As explained in CERES-Maize, the initial ear weight was considered as 16.7% of stem weight. Ear growth and weight were calculated using equations published by Jones and Kiniri (1986).

$$EG = 0.22 \times GDD \tag{21}$$

$$EW = \sum_1^n EG \tag{22}$$

n = number of days in particular stage

where, *EG* is ear growth rate (g/ear/day), *GDD* is daily growing degree days which starts from silking and *EW* is ear weight.

(4) Grain filling

Temperature is also the main driver for the computation of the potential daily rate of grain weight. Leaf senescence increases while grain filling increases. Grain filling (*GF*) calculations were based on Jones and Kiniry (1986) as,

$$GF = TFFILL \times NGP \times G \times 0.001 \tag{23}$$

Where, *GF* is daily grain growth (g/plant/day), *TFFILL* is grain growth development factor affected by temperature (0-1), *GNP* is number of grains per plant (grains/plant) and *G* is potential grain growth rate (mg/grain/day). Then the number of grains (*GNP*) was obtained as,

$$NGP = G2 \times APR/7200 + 50 \tag{24}$$

where, *G2* is a parameters representing the potential grains number per plant (grains/plant) typical of the simulated variety and *APR* is average photosynthetic rate during pollination (%). Then, the average photosynthetic rate during pollination was calculated by,

$$APR = (CP \times 1000)/NDP \times 3.4/5 \tag{25}$$

Where *CP* is cumulative photosynthesis during pollination (g/plant), *NDP* is number of days taken for pollination.

2.2 Model evaluation

The NWMSim is implemented using object-oriented programming language in Microsoft Visual Basic on .NET platform. The data used to validate the model were collected by the College of Agronomy, Northwest A&F University in Yangling, Xi'an, China for the period of five years (five cropping cycles) including 2005, 2006, 2007, 2009 and 2011. Xi'an is one of the large scale maize growing areas in Northwest China. Weather (maximum and minimum temperature, solar radiation, photoperiod), soil (soil moisture content, wilting point), management (sowing date and depth, plant spacing, variety name, plant density) and site (latitude, longitude, elevation) data were used as input parameters. The longitude, latitude and elevation of the area are E 108° 10', N 34° 21' and 454.8 m respectively. In the area, all over the five cropping cycles, the sowing date varies from 8th - 12th June and the planting depth varies from 8-10 cm. The whole cropping cycle ranges from early June to mid October. Plant spacing and density are 60 cm and 6 plants/m² respectively. The common maize variety in the area is *Zhengdan958* which is one of the leading growing varieties in all over the China. The experimental field was supplied with 40 m³/ha of water, 300 kg/ha of Nitrogen (N) and 225 kg/ha of Phosphorus (P) to avoid water and nutrient stresses in order to ensure a potential maize yield. As a part of this research we have developed a weather generator (CMWSim) to generate weather data including precipitation and maximum and minimum temperature. Design, implementation and validation results of CMWSim are not explained here as CMWSim published in elsewhere (Rajawatta *et al.*, 2014). However we used generated maximum and minimum temperature by CWMSim as weather inputs for NWMSim. In the mean time we did not use the precipitation values generated by CWMSim as the NWMSim considers only potential yield without taken the water stress into account.
The model simulates final grain yield, daily growth and development including leaf area, leaf area index, ear growth, grain growth, grain weight and yield. Each and every stage includes algorithms for calculations of individual function because it minimizes the errors in the model. Simulated results of NWMSim were compared with five year field data. Average weather profile in five cropping cycles is shown in Tab. 2.

The NWMSim model is statistically analyzed for reliability. The accuracy of NWMSim model in reproducing observed yield and LAI values was analyzed using the following evaluation metrics MAE (Mean Absolute Error), EF (model efficiency), RRMSE (Root Mean Square Error) and R^2 (linear regression analysis). Other output variables referring to development and growth were evaluated using the determination coefficient (R^2). Error values (MAE and RRMSE) and model efficiency (EF) were calculated using (Loague and Green, 1991; Smith *et al.*, 1996),

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(|S_i - O_i|) \tag{26}$$

$$EF = \frac{\left[\sum_{i=1}^{n}(O_i-\bar{O})^2-\sum_{i=1}^{n}(S_i-O_i)^2\right]}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \tag{27}$$

Year	Tmax (°C)	Tmin (°C)	Cumulative Solar radiation (MJ/m²)
2005	27.19	18.15	1867.63
2006	28.34	19.01	2135.24
2007	26.23	17.65	1696.68
2009	27.48	18.11	1839.73
2011	26.48	17.46	1847.6

Tab. 2 - Weather profile (total solar radiation; mean daily maximum Tmax, and minimum, Tmin) temperatures experienced by the crop within the cropping cycle, during the five years of field experiments.
Tab. 2 - Profilo climatico (radiazione solare totale; temperatura media massima giornaliera Tmax, e minima, Tmin) durante il ciclo colturale, nei 5 anni di sperimentazione in campo.

$$RRMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2\right]^{0.5} \times \frac{100}{\bar{O}} \qquad (28)$$

where, n is sample number, S_i is the simulated values, O_i is observed values and $\bar{O}$ is the mean value of observed values. MAE and RRMSE values are close to zero, and EF value and R^2 are close to one indicating that the simulated values are closely fitted to the observed values, and the model performs better. Further, if EF value equals to one, the model is considered as a perfect model.

3. RESULTS AND DISCUSSION

The actual sowing dates of observed five years ranged between the 8th and 12th of June. Sowing date is an input of the model and it corresponds to the day of the year at which the simulation is initialized. The model gives a number as 'Day of year' for sowing date. NWMSim simulates number of days for each and every stage, day of year and total number of days. The detailed description of the observed and simulated number of dates for different stages of maize life cycle is shown in Tab. 3 and Fig. 1. Results reveal that the number of days for different stages in different years are simulated in acceptable level while a slightly differ in harvesting stage (Tab. 3). However the coefficient of determination (R^2=0.974) shown a markedly positive agreement between simulated and observed data for all the phenological stages considered.

The development variables total dry matter (Fig. 2(c) and Fig. 3) and stem weight (Fig. 2(d) and Fig. 4) were compared and analyzed statistically to evaluate the model. The same pattern and shape can be seen in the simulated total dry matter and stem weight (Fig. 2(c) and Fig. 2.(d)). The mean values of observed and simulated total dry matter

Stage	2005		2006		2007		2009		2011	
Emergence	Jun 19	Jun 18	Jun 17	Jun 15	Jun 15	Jun 14	Jun 17	Jun 16	Jun 17	Jun 17
Day of year	170	169	168	166	166	165	168	167	169	168
No of days	7	6	7	5	7	6	7	6	7	6
3-leaf unfolding	Jul 1	Jun 30	Jun 29	Jun 28	Jun 27	Jun 29	Jun 29	Jun 28	Jun 30	Jul 1
Day of year	182	181	180	179	178	180	180	179	181	182
No of days	12	12	12	13	12	15	12	12	12	14
Jointing	Jul 17	Jul 14	Jul 15	Jul 11	Jul 13	Jul 12	Jul 15	Jul 10	Jul 17	Jul 15
Day of year	198	195	196	192	194	193	196	191	198	196
No of days	16	14	16	13	16	13	16	12	16	14
Booting	Aug 3	Jul 27	Aug 1	Jul 23	Jul 30	Jul 27	Aug 1	Jul 29	Aug 3	Jul 28
Day of year	215	208	213	204	211	208	213	210	215	209
No of days	17	13	17	12	17	15	17	14	17	13
Spinning	Aug 19	Aug 12	Aug 17	Aug 8	Aug13	Aug 14	Aug 15	Aug 16	Aug 19	Aug 15
Day of year	231	224	229	220	227	226	229	228	231	227
No of days	16	16	16	16	16	18	16	17	16	18
Harvest	Oct 3	Oct 1	Oct 1	Sep 25	Sep 29	Oct 6	Oct 1	Oct 3	Oct 3	Oct 21
Day of year	276	274	274	268	272	279	274	276	276	294
No of days	45	50	45	48	45	53	45	54	45	67

Tab. 3 - Comparison between Observed (obs.) and simulated (Sim.) number of days for different phenological stages within the five cropping cycles analyzed.
Tab. 3 - Confronto tra numero di giorni Osservati (Obs.) e Simulati (Sim.) per le differenti fasi fenologiche nei 5 anni di cicli colturali analizzati.

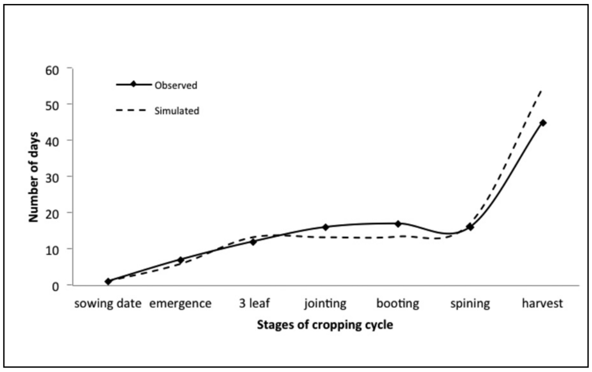

Fig. 1 - Comparison between observed and simulated number of days required to reach each of the considered phenological stages along the cropping cycle. Results are presented as an average of the 5-years data.
Fig. 1 - Confronto tra numero osservato e simulato di giorni richiesti per raggiungere ciascuna delle fasi fenologiche durante il ciclo colturale. I risultati sono presentati come media di 5 anni.

were 96.6 and 98 g/plant respectively. The Mean absolute error (MAE) was 0.04 and determination coefficient (R^2) was 0.89 for total dry matter. The mean values of observed and simulated stem weight were 11.72 and 12.39 g/plant respectively. The Mean absolute error (MAE) is 0.046 and determination coefficient (R^2) was 0.83. Above values show the strength of the model fitting.

The growth variables leaf area index (LAI) and yield were also analyzed statistically to evaluate the NWMSim model. The pattern and shape of simulated LAI is much closer to observed values until it reaches to maximum value (EF=0.96, MAE=0.0.11 and RRMSE=20%), (Fig 2(a) and Tab. 4). Although LAI is slightly overestimated at the last stage of maize life cycle, no significant difference was found (R^2=0.88, Fig. 5). However the maximum LAI was observed on the same day (maximum LAI = 5.1 and 4.9 cm²/cm²) for both

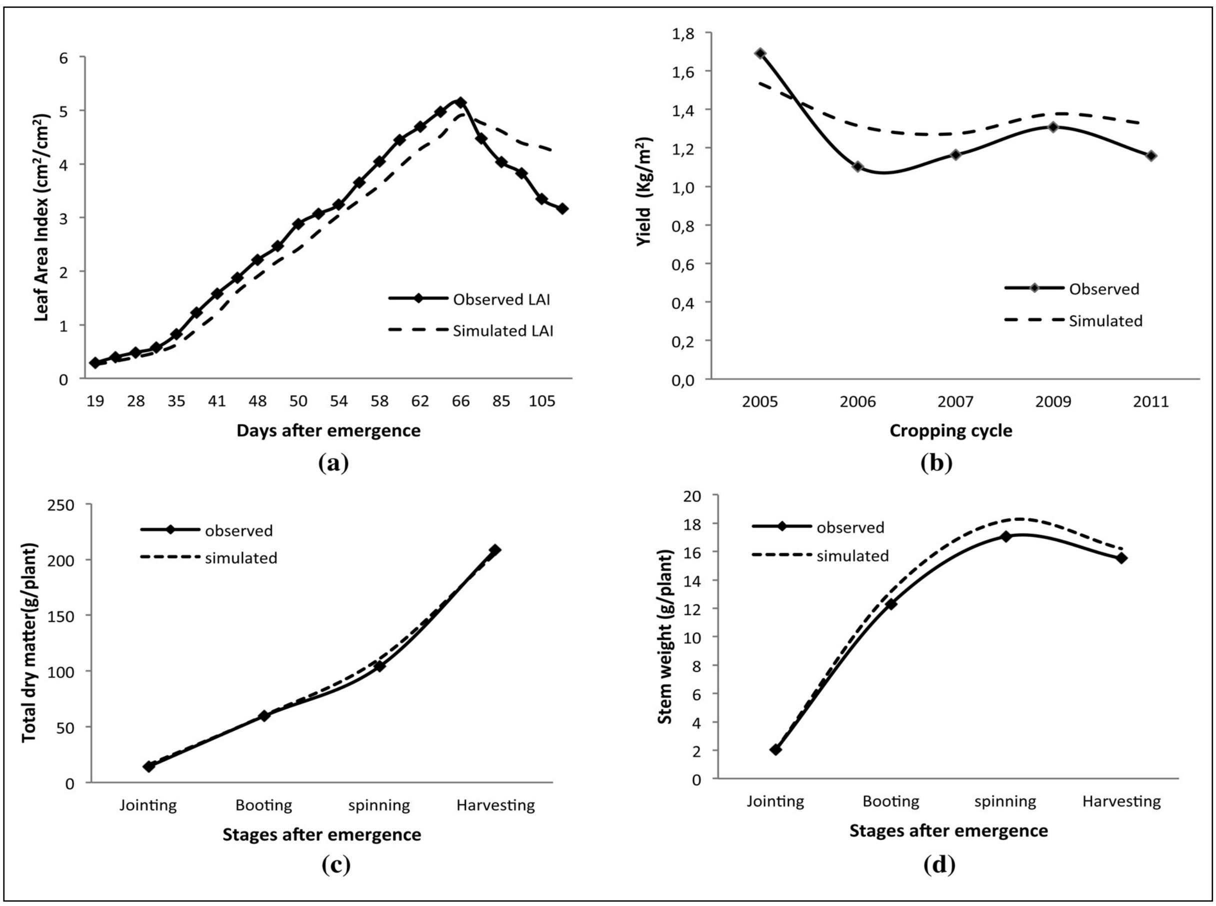

Fig. 2 - Comparison between observed and simulated variables within the cropping cycle. Results are presented as an average of the 5-years data. (a) Leaf area Index profiles (b) Grain yield (c) Total dry mass accumulation (d) Stem weight accumulation.
Fig. 2 - Confronto tra variabili osservate e simulate durante il ciclo colturale. I risultati sono presentati come media di 5 anni. (A) Indice di Area Fogliare (b) resa in granella (c) sostanza secca totale cumulata (d) peso cumulato degli steli.

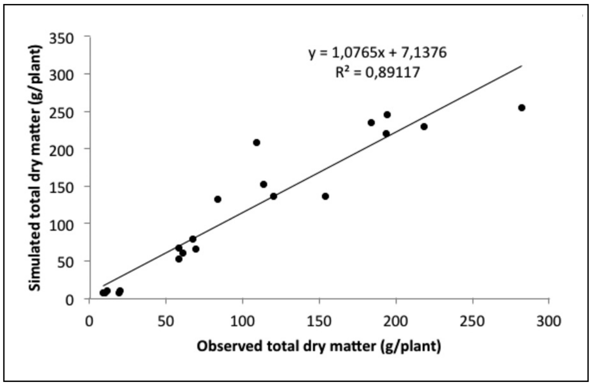

Fig. 3 - Regression between observed and simulated values of total dry matter (g/plant) within the 5-years cropping cycles.
Fig. 3 - Regressione tra valori osservati e simulati di sostanza secca totale (g/pianta) nei 5 anni di studio.

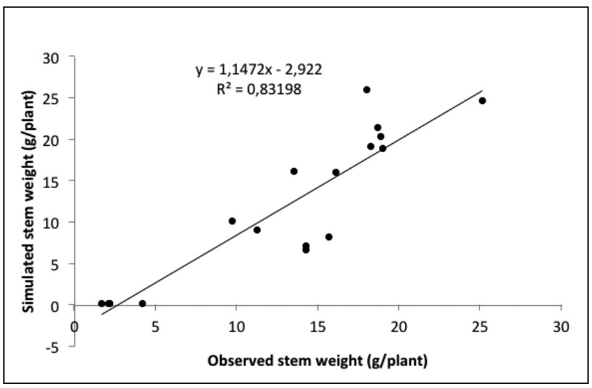

Fig. 4 - Regression between observed and simulated values of stem weights (g/plant) within the 5-years cropping cycles.
Fig. 4 - Regressione tra valori osservati e simulati del peso degli steli (g/pianta) nei 5 anni di studio.

observed and simulated values. As LAI is used to predict photosynthetic primary production of a particular crop, it would be one of the most important factors considered for crop growth modeling. The yield is the most important factor in

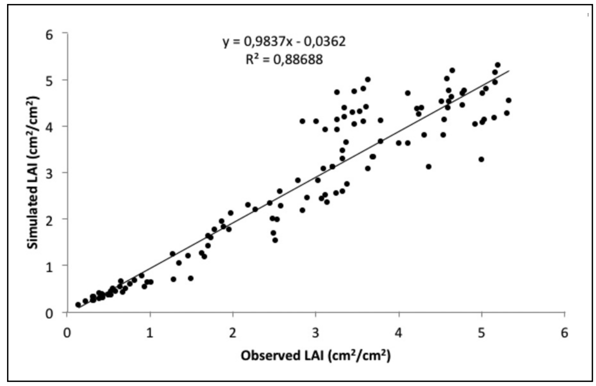

Fig. 5 - Regression between observed and simulated values of leaf area index (LAI) profiles within the 5-years cropping cycles.
Fig. 5 - Regressione tra valori osservati e simulati dellíIndice di Area Fogliare (LAI) nei 5 anni di studio.

evaluation process to check the performance of the model. The mean values of observed and simulated number of grains per plant were 495 and 489 respectively. The number of ears per unit area is equal to plant density, thus the ears per unit area (ears/m^2) was 6. Comparisons and statistical analysis of grain yield are shown in Fig 2(b) and Tab. 4. Mean grain yield for simulated and observed are 1.4Kg/m^2 and 1.3Kg/m^2 respectively. Although the simulated grain yield for 2006, 2007 and 2011 cropping cycles were slightly overestimated (Fig 2(b)), the statistical analysis has shown a strong relationship with observed values (Tab. 4).

4. CONCLUSION

Our intended aim was to develop a user-friendly windows-based growth model (NWMSim) to estimate region-specific accurate maize yield using fewer input parameters, especially for Northwest region in China. The target was achieved successfully developing the model which simulates the maize growth and development to predict the

	Yield (Kg/m^2)	Leaf Area Index (cm^2/ cm^2)
Modeling efficiency (EF)	0.98	0.96
Mean Absolute Error (MAE)	0.11	0.11
Root Mean Square Error (%) (RRMSE)	11.68	20.0
Determination coefficient (R^2)	0.94	0.88

Tab. 4 - Modeling efficiency, Mean Absolute Error, Root Mean Square Error and Determination coefficient of Observed and simulated Yield and Leaf Area Index.
Tab. 4 - Efficienza della modellazione, Errore assoluto medio, Radice dell'errore quadratico medio, Coefficiente di determinazione di resa e Indice di Area Fogliare, osservati e simulati.

final grain yield. The validation was done using five years collected data by College of Agronomy, Northwest A&F University. NWMSim simulated accurately all the considered growth and development variables on daily basis including leaf area index, total dry matter, stem weight, number of grains per plant and number of days per stage. When compared with the five years field data, a strong relationship was shown for all stage-wise growth variables while the grain yield was slightly over estimated only for three cropping cycles (2006, 2007 and 2011). However the statistical analysis was clearly shown that there is no significant difference between observed and simulated final grain yield for over five years with R^2 value of 0.94 and EF=0.98. Based on the results and the comparisons of simulated and observed values, it appears that the model can be used as a prediction tool in maize cultivation and also an economic management tool in economic planning in regional level. Further the model provides positive evidence that it could be used as a research tool for maize growth and development. As the first version of the NWMSim, it is evaluated only for Xi'an in Northwest region in China. Further, field trials to be done for other locations of Northwest China to accurately validate the model. The model simulates through one cropping cycle (one year), and therefore it should be expanded to simulate multiple cropping cycles. The model simulates the potential maize production, and therefore it has not been evaluated under water and nutrients limited conditions. Further improvements of the model should be focused on the implementation of algorithms reproducing the limitations due to water and nutrients shortage on maize productions to increase the accuracy and prediction capabilities. Integrated weather generator helps to consider multiple cropping years and water stress conditions as it predicts the weather records accurately including precipitation.

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REFERENCES

Bassu S., Brisson N., Durand J.-L., Boote K., Lizaso J., Jones J.W., Rosenzweig C., Ruane A.C., Adam M., Baron C., Basso B., Biernath C., Boogaard H., Conijn S., Corbeels M., Deryng D., De Sanctis G., Gayler S., Grassini P., Hatfield J., Hoek S., Izaurralde C., Jongschaap R., Kemanian A.R., Kersebaum K.C., Kim S.H., Kumar N.S., Makowski D., Müller C., Nendel C., Priesack E., Pravia M.V., Sau F., Shcherbak I., Tao F., Teixeira E., Timlin D., Waha K., 2014. How do various maize crop models vary in their responses to climate change factors? Glob. Change Biol., 20, no. 7, 2301-2320, doi:10.1111/gcb.12520

Belfield S., Brown C., 2008. Field crop manual: Maize; A guide to upland production in Cambodia, New south Wales department of primary industries. ISBN 9780734718822

Ciampitti I.A., Vyn T.J., 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review, field crops research 133 (2012) 48-67.

Dejonge K.C., Ascough J.C., Andales A.A., Hansen N.C., Garcia L.A., Arabi M., 2012. Improving evapotranspiration simulations in the CERES-Maize model under limited irrigation. Agricultural water management, 115, 92-103.

Drouet J.L., Pagès L., 2003. GRAAL: a model of GRowth, Architecture and carbon Allocation during the vegetative phase of the whole maize plant: Model description and parameterization, Ecological modeling 165(2003) 147-173.

FAOSTAT, (2013). Food and Agricultural commodities production. [online] Available at: < http://www.faostat.fao.org/>

Jones C.A., Kiniry J.R., 1986. CERES-Maize: A simulation model of maize growth and development. Texas A & M university press, College station, Texas, USA. 194 pp.

Kropff M.J., van Laar H.H., 1993. Modelling crop-weed Interactions. CAB international, Wallingford, UK.

Liu H., Yang J., He P., Bai Y., Jin J., Craig F.D., Zhu Y., Yang X., Li W., Xie J., Yang J., Hoogenboom G., 2012. Optimizing Parameters of CSM-CERES-Maize Model to Improve Simulation Performance of Maize Growth and Nitrogen Uptake in Northeast China, Journal of Integrative Agriculture, 2012, 11(11): 1898-1913.

Loague K., Green R. E., 1991. Statistical and graphical methods for evaluating solute transport models: overview and application, Journal of contaminant hydrology, vol 7, pp. 51-73.

Maselli F., Conse C., Petkov L., Gilabert M.A., 1992. Use of NOAA-AVHRR NDVI data for environmental monitoring and crop forecasting in the Sahel. Preliminary results, Int. J. Remote sensing, 1992, vol. 13, NO. 14, 2743-2749.

Mastrorilli M., Katerji N., Nouna B.B., 2003. Using the CERES-Maize model in a semi-arid Mediterranean environment. Validation of three revised versions, Europ. J. Agronomy 19 (2003) 125/134.

McCown R.L., Hammer G.L., Hargreaves J.N.G., Holzworth D.P., Freebairn D.M., 1996. APSIM: A novel software system for model development, model testing and simulation in agricultural systems research. Agricultural Systems 50: 255-271.

Meng Q., Hou P., Wu L., Chen X., Cui Z., Zhang F., 2012. Understanding production potentials and yield gaps in intensive maize production in China. Field crops research 143 (2013) 91-97.

Nouna B.B., Katerji N., Mastrorilli M., 2000. Using the CERES-Maize model in a semi-arid Mediterranean environment. Evaluation of model performance, European Journal of Agronomy 13 (2000) 309-322.

Penning de Viries F.W.T., Jansen D.M., ten Berge H.F.M., Bakema A., 1989. Simulation of ecophysiological processes of growth in several annual crops, Pudoc, Waganingen, Netherland.

Priya S., Hibasaki R., 2001. National spatial crop yield simulation using GIS-based crop production model. Ecological Modelling, Volume 136, Issues 2-3.

Rajawatta K.M.W., Dongjian He, Piyaratne M.K.D.K., 2014. CMWSim: development and evaluation of probability-based weather generating software. Italian journal of Agrometeorology, 3/2014: 5-13.

Robert G.H., Emerson D.N., Richard R.J., Samuel R.A., 2000. Modern corn and soybean production, First edition.

Smith J., Smith P., Addiscott T., 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models, Evaluation of soil organic matter models, NATO ASI series, vol. 38, pp. 181-199.

UCIPM, 2015. University of California Agriculture, and Natural resources, statewide integrated pest management program. [online] Available at: < WEATHER/ddconcepts. html #note>

Van Diepen C.A., Wolf J., van Keulen H., Rappoldt C., 1989. WOFOST: a simulation model of crop production. Soil Use Manage. 5, 16-24.

Wang J, Li X, Lu L and Fang F, 2013. Estimating near future regional corn yields by integrating multi-source observations into a crop growth model, European journal of Agronomy, 49, 126-140.

Xiong W., Matthews R., Holman I., Lin E., Xu Y., 2007. Modelling China's potential maize production at regional scale under climate change. Climatic Change (2007) 85:433-451.

Yang H.S., Dobermann A., Cassman K.G., Walters D.T., Grassini P., 2013. Hybrid-Maize (ver. 2013.4). A simulation model for corn growth and yield. Nebraska Cooperative Extension, University of Nebraska-Lincoln, Lincoln, NE.

Yang H.S., Dobermann A., Lindquist J.L., Walters D.T., Arkebauer T.J., Cassman K.G., 2004. Hybrid-maize- a maize simulation model that combines two crop modeling approaches, Field crops research 87, pp. 131-154.

Zand-Parsa S.h., Sepaskhah A.R., Ronaghi A., 2006. Development and evaluation of integrated water and nitrogen model for maize, Agricultural Water Management 81(2006) 227-256.

Zhang J., 2011. Chinaís success in increasing per capita food production, Journal of Experimental Botany, Vol. 62, No. 11, pp. 3707-3711.