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**Processing Tomato Production in Northeastern Italy: Environmental  
and  
Agronomic Assessment Using CSM-CROPGRO-Tomato Model**

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## Declaration

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(\_\_\_\_\_ / Maha Lotfy Mohamed Elsayed / July 2011)

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## Dedication

I dedicate this work

to my family who are  
always the source of  
ambition, power, and  
love...

to my husband who is the  
source of tender without  
limits...

Maha

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## List of Abbreviations

<b>AUG</b>	Augusto F1 processing tomato variety
<b>FR</b>	Fruiting stage of tomato plant growing cycle
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>LAI</b>	Leaf area index
<b>M</b>	Mulched soil
<b>MaxT</b>	Maximum temperature
<b>MinT</b>	Minimum temperature
<b>NM</b>	Non-mulched soil
<b>NPT</b>	NPT 63 processing tomato variety
<b>SAF</b>	Safaix processing tomato variety
<b>SPAD</b>	Soil Plant Analysis Development, an instrument to measure leaves chlorophyll content
<b>SRAD</b>	Global solar radiation
<b>TD</b>	Transplanting date
<b>TIZ</b>	Tiziano F1 processing tomato variety
<b>Veg</b>	Vegetative stage of tomato plant growing cycle

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## ***ABSTRACT***

The Italian processing tomato has a major dominance in the global market but few studies have been conducted using a cropping systems analysis approach for this crop. The overall goal of this project was to evaluate the Cropping System Model (CSM)-CROPGRO-Tomato of the DSSAT (Decision Support System for Agrotechnology Transfer) software with experimental data obtained from field experiments that were conducted at the experimental farm in Legnaro, northeastern Italy in 2009 and 2010.

The experiments encompassed four transplanting dates starting on 21<sup>st</sup> of April in 2009 and on 29<sup>th</sup> of April in 2010 and with ten-day intervals. Mulched and non-mulched plots, and four local processing tomato (*Lycopersicon esculentum* Mill.) varieties: Augusto F1 (AUG) and Tiziano F1 (TIZ) from De Ruiters company; and NPT 63 (NPT) and Safaix (SAF) from S&G company were also compared.

A comparison of yield for the different transplanting dates showed that earlier transplanting dates increased yield for all varieties, while there was a significant higher yield for NPT variety than the other three varieties. The moderate rainy season in 2009 gave a significant difference between mulched and non-mulched plots, with higher plant growth for mulched conditions. The rainy season in 2010 reduced the effect of both mulching the soil and irrigation on growth, development, and yield.

Calibration of CSM-CROPGRO-Tomato model using the non-mulched treatments showed that d-Stat values between observations and model simulation for different parameters using the four varieties ranged from 0.562 to 0.964 at TD1, from 0.915 to 0.992 at TD2, from 0.566 to 0.990 at TD3, and from 0.733 to 0.998 at TD4. Parameters used at calibration phase were total dry matter, fruits dry matter, vegetative dry matter, number of fruits, harvest index and leaf area index. Values of d-Stat for model calibration were lower for leaf area index, which ranged from 0.511 to 0.924. Model calibration using TD1 gave acceptable simulation, whereas it was quite high with the other transplanting dates. This study showed that it is possible, under northeastern Italian conditions, to apply the model for simulating growth and yield of different processing tomato varieties for different

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production seasons and under different weather conditions. Further experimental work is needed, anyway, in order to evaluate the model performance.

Forty years of future projected daily weather datasets from 2011 to 2050 were used to evaluate the performance of calibrated CSM-CROPGRO-Tomato model under different weather conditions. ENEA and MPI were the two future weather scenarios used in order to evaluate processing tomato growth under changed climate conditions. Plants were affected more seriously with MPI scenario as it had sharper changes. At early transplanting, plants will be more adapted to new weather conditions so they will remain at a stable production level in almost all years. Lack of rain using MPI scenario, coupled with higher temperature, will cause a reduction in yield and a need for more amount and frequency of irrigation. Global solar radiation and minimum and maximum temperature will affect growing cycle length. There is a negative correlation between growing cycle to maturity length and values of both minimum and maximum temperature. Yield will be also affected negatively by season average minimum temperature. As low was the average temperature during the growing season as long was growing cycle.

Despite the good results with the calibration of the model, further studies and research are needed in order to better adapt the internal parameters of the software to the different varieties available and the specific conditions of northern Italy. This indicates that under northeastern Italian conditions it would be possible to use the model and to simulate the possible yield of different processing tomato varieties at different seasonal and weather conditions.

**Keywords:** *Lycopersicon esculentum* Mill., northeastern Italy, DSSAT, crop simulation, calibration, validation, climate change scenarios.

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## **RIASSUNTO**

Il pomodoro da industria italiano ha una posizione dominante nel mercato mondiale, ma pochi studi sono stati condotti, per questa coltura, utilizzando un approccio di analisi dei sistemi culturali. L'obiettivo generale di questo progetto era quello di valutare il modello CSM-CROPGRO-Tomato del DSSAT (Decision Decision Support System for Agrotechnology Transfer) software con i dati sperimentali ottenuti da prove di campo condotte presso l'azienda agricola sperimentale di Legnaro, nord-est di Italia nel 2009 e 2010.

Gli esperimenti comprendevano quattro date di trapianto, a partire dal 21 aprile nel 2009 e dal 29 aprile nel 2010 e con intervalli di dieci giorni, confrontando inoltre trattamenti di pacciamatura a confronto con testimoni non pacciamati, e quattro diverse varietà di pomodoro da industria (*Lycopersicon esculentum* Mill) : Augusto F1 (AUG) e Tiziano F1 (TIZ) forniti dalla Ditta De Ruiters, e NPT 63 (NPT) e Safaix (SAF) forniti da S&G.

Un confronto tra la resa per le diverse date di trapianto ha mostrato che un anticipo del momento di trapianto aumenta la resa per tutte le varietà. Si è verificata inoltre una resa significativamente superiore per la varietà NPT rispetto alle altre tre varietà. La stagione 2009, caratterizzata da piovosità moderata, ha indotto una significativa differenza tra tesi pacciamate e non pacciamate, con ritmo di crescita più elevato per i trattamenti con pacciamatura. La stagione 2010, caratterizzata da elevata piovosità, ha invece coperto l'effetto della pacciamatura del suolo e quindi dell'intensità della irrigazione sia sulla crescita sia sullo sviluppo e resa.

La calibrazione del modello CSM-CROPGRO-Tomato, utilizzando i trattamenti non pacciamati, ha mostrato che i valori d-Stat compresi tra osservazioni e simulazione del modello per diversi parametri utilizzando le quattro varietà variava tra 0,562 e 0,964 a TD1, tra 0,915 e 0,992 a TD2, tra 0,566 e 0,990 a TD3, e tra 0,733 a 0,998 a TD4. I parametri utilizzati in fase di calibrazione sono stati sostanza secca di pianta totale, sostanza secca di frutti, sostanza secca delle strutture vegetative, il numero di frutti, indice di raccolta e indice della superficie fogliare. I valori di d-Stat per la calibrazione del modello sono state

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inferiori per l'indice di area fogliare, che variavano tra 0,511 e 0,924. La calibrazione del modello di simulazione per la prima data di trapianto è stata accettabile, ma risultati migliori sono stati ottenuti usando le altre date di trapianto.

Questo studio ha dimostrato che è possibile applicare il modello, e in diverse condizioni meteorologiche tipiche del nord est italiano. Comunque, sono necessari ulteriori lavori sperimentali per approfondire le valutazioni delle prestazioni del modello.

Quarant'anni di dati meteorologici giornalieri stimate per il futuro (2011-2050) sono stati utilizzati per valutare le prestazioni del modello calibrato CSM-CROPGRO-Tomato in condizioni di cambiamenti climatici. ENEA e MPI sono stati i due scenari meteorologici utilizzati per valutare la risposta di crescita del pomodoro in condizioni di cambiamento climatico. Le piante sono state influenzate più seriamente con lo scenario MPI che presentava variazione occidentale. Al primo trapianto, le piante saranno più adattate alle nuove condizioni climatiche in modo che rimarrà a un livello di produzione stabile in quasi tutti gli anni. La carezza di pioggia ipotizzata nello scenario MPI accoppiata con temperature superiori causerà una diminuzione delle rese e la necessità di maggiori irrigazioni. I parametri che hanno influenzato maggiormente le simulazioni sono stati la radiazione solare globale e la temperatura minima e massima che influiscono sulla lunghezza del ciclo e il numero di giorni tra fruttificazione e maturazione. E' stata trovata una correlazione negativa tra lunghezza del ciclo di crescita e valori della temperatura minima e massima. La resa è influenzata negativamente anche dalla temperatura minima e massima della stagione. Più bassa è stata la temperatura media durante il periodo di crescita, più corto è stato il ciclo vegetativo.

Nonostante i buoni risultati ottenuti con la calibrazione del modello, ulteriori studi e ricerche sono necessari al fine di meglio adattare i parametri interni del software alle diverse varietà a disposizione e alle condizioni specifiche del nord Italia. Ciò indica che in condizioni tipiche del nord-est di Italia sarebbe possibile utilizzare il modello per simulare la resa delle diverse varietà di pomodoro a differenti condizioni stagionali e meteo.

**Parole chiave:** *Lycopersicon esculentum* Mill, nord-est di Italia, DSSAT, la simulazione delle colture, la calibrazione, scenari di cambiamenti climatici.



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# **Chapter 1**

## **Literature Review**

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# 1. Literature Review

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## 1.1. Production of tomato at global, Mediterranean, and Italian levels

The global production of tomatoes (fresh and processed) has increased by about 300% in the last four decades (Costa and Heuvelink, 2005). At global scale, more than 141.4 million tons per year of tomato are produced (FAO, 2009). There are more than 10,000 varieties of tomatoes distributed all over the world. This quite high production annually is due to its nutritional complimentary value. Tomatoes are rich in vitamins A and C and fiber, and are cholesterol free. Furthermore, new medical research suggests that the consumption of lycopene - the compounds responsible for color of tomatoes - may prevent cancer (Liu *et al.*, 2006; Breemen and Pajkovic, 2008).

According to FAO database updated in 2009, the top six producers of tomatoes worldwide are China, United States, India, Turkey, Egypt, and Italy, respectively. The Mediterranean annual production amount of tomato in 2009 was more than 29.9 million tons, which represents about 21% of the global production.

Italy produces more than 6.4 million tons (54506.4 kg ha<sup>-1</sup>) of tomato annually from an area of 117100 ha, which represents 21.4% of Mediterranean production and about 5% of the global production (FAO, 2009). It dominates the global processed tomato products market. World Processing Tomato Council in 2006 stated that Italy produces and supplies 18% of total world production in 2005 of processing tomato (*Lycopersicon esculentum* Mill.), and northern Italy contributes in more than 40% of its production (AMITOM, 2006). Cultivation in the north is highly mechanized and uses hybrid seeds and transplants, resulting in higher yields (75–100 t ha<sup>-1</sup>) than in the south (about 65 t ha<sup>-1</sup>) (AMITOM, 2003). Planting starts in early May, harvest commences in mid July and the season ends by the middle or end of September (Santella, 2003).

The tomato belongs to the family *Solanaceae* (also known as the nightshade family), genus *Lycopersicon*, subfamily *Solanoideae* and tribe *Solaneae* (Taylor, 1986). In 1753 the Swedish botanist Linnaeus named it *Solanum lycopersicon*, but 15 years later Philip Miller replaced the Linnaean name with *Lycopersicon esculentum* (Taylor, 1986).

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Although taxonomists have recently reintroduced its original name, *Solanum lycopersicon* (Heiser and Anderson, 1999), the commonly accepted and still valid name is *Lycopersicon esculentum*.

The *Lycopersicon* genus includes a relatively small collection of species: the cultivated tomato *L. esculentum* Mill. and several closely related wild *Lycopersicon* species (Taylor, 1986). The cultivated tomato reached its present status after a long period of domestication.

All related wild species of tomato are native to the Andean region that includes parts of Chile, Colombia, Ecuador, Bolivia and Peru (Sims, 1980). Although the ancestral forms of tomato grew in the Peru–Ecuador area, the first extensive domestication seems to have occurred in Mexico (Sims, 1980; Harvey *et al.*, 2002). The Spanish introduced the tomato into Europe in the early 16th century (Harvey *et al.*, 2002). Since the mid-16th century tomatoes have been cultivated and consumed in southern Europe, though they only became widespread in north-western Europe by the end of the 18th century (Harvey *et al.*, 2002).

Costa and Heuvelink (2005) stated that tomatoes are one of the most widely eaten vegetables in the world. Their popularity stems from the fact that they can be eaten fresh or in a multiple of processed forms. Three major processed products are: (i) tomato preserves (e.g. whole peeled tomatoes, tomato juice, tomato pulp, tomato purée, tomato paste, pickled tomatoes); (ii) dried tomatoes (tomato powder, tomato flakes, dried tomato fruits); and (iii) tomato-based foods (e.g. tomato soup, tomato sauces, chilli sauce, ketchup).

Tomatoes are commonly used as a ‘model crop’ for diverse physiological, cellular, biochemical, molecular and genetic studies because they are easily grown, have a short life cycle and are easy to manipulate (e.g. by grafting, 2 J.M. Costa and E. Heuvelink cuttings) (Kinet and Peet, 1997). Therefore, the tomato is an excellent tool to improve knowledge on horticultural crops (Taylor, 1986; Kinet and Peet, 1997).

The tomato industry is one of the most advanced and globalized horticultural industries. Most production is located in temperate zones (<http://www.tomatonews.com>) that have long summers and mainly winter precipitation. However, cultivation practices, the ratio between production for processing or fresh consumption and the organization and structure of the industry and markets differ widely among countries (Costa and Heuvelink, 2005).

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European tomato production can be divided into two major production systems. The Northern system is capital intensive, using modern technology (greenhouse structures, climate control, crop protection). It is highly productive and focused on fresh tomato production. The Southern (Mediterranean) system produces fruit in the open field for processing, and in plastic-covered structures for fresh consumption (Harvey *et al.*, 2002).

## **1.2. Filed-grown Processing Tomato Varieties (*Lycopersicon esculentum* Mill.)**

The major traits of processing tomatoes are determinate growth, dwarf habit, concentrated and uniform fruit set and ripening, tough skins, and high soluble solids content (George, 1999). Processing tomatoes are grown in open-field systems and are usually direct drilled, but transplants are commonly used in more advanced production systems. They do not require trellising or staking and are harvested mechanically.

Varieties used in this study are for processing tomato and they are suitable to be grown in the open field. Their physical and chemical characteristics are explained here below (S&G, 2009; De Ruiter Seeds, 2009):

### **1.2.1. Augusto F1 Variety**

Hybrid-type extended-cycle average high in lycopene. Plant is determined, vigorous, well-covering and suitable for mechanical harvesting. Plant has dark green color and is very rustic. The fruit is cylindrical from the mean and weigh 75-80 gr. Fruits are very consistent, with a taproot almost absent and a red flesh colour.



### **1.2.2. Tiziano F1 Variety**

Hybrid cycle with medium-late plant vigorous, semi-erect posture. Fruits are high in Lycopene. It has excellent coverage of the fruit and the overall health of the plant. It has good ability to attach in any condition. The berries are of square shape and of a bright red colour. The fruits are also particularly strong with a good seal to



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overmaturation. Average Weight per fruit is 80-90 grams. It has very high productivity and good range of resistances complement the profile of this new hybrid.

### **1.2.3. Safaix and NPT 63 Varieties**

Hybrid with early segment, characterized by rustic plant, healthy and balanced diet that adapts well to different soil types. The force is medium and covering the fruit is very good. The berries are oval, oblong, jointless sized and characterized by consistency and sustaining (70-80 gr.). Good colouring. The potential production is high and the ripening is concentrated. It has good behaviour in fertigation.



Typically, node formation of field-grown tomato ceases after about twenty nodes whereas, for greenhouse tomato, node formation continues throughout the entire growth period (Scholberg, 1994).

## **1.3. Influence of plastic mulch on growth and yield of field grown tomatoes**

Tomatoes require a high water potential for optimal vegetative and reproductive development (Waister and Hudson, 1970). In case of deficit of irrigation, there is a need to adopt appropriate technology to conserve the water in the soil profile and its best possible utilization for plant growth (Mukherjee *et al.*, 2010). Mulching (organic and inorganic) is an appropriate approach to enhance efficiency level of irrigation besides improving crop yield (Sarkar *et al.*, 2007). Reduction in evaporation from crop field through polyethylene mulch enhances both productivity and water use efficiency (Lie *et al.*, 2004). Mulch works as a barrier for water evaporation (Ngouajio *et al.*, 2007). The benefits associated with use of plastic mulches include higher yields, earlier harvests, improved weed control, and increased efficiency in the use of water and fertilizers (Lamont, 1993). Plastic mulches affect plant microclimate by modifying the soil energy balance and by restricting soil water evaporation (Liakatas *et al.*, 1986). Modification of these microclimate factors influence soil temperature, which affects plant growth and yield (Voorhees *et al.*, 1981). Increased root-zone temperature (RZT) is one of the main benefits associated with use of plastic mulches (Wien and Minotti, 1987).

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Organic (plant materials) and synthetic mulches (plastic of different colors like white, black, red, green, yellow, and transparent) are widely used in vegetable production for their efficacy to conserve soil moisture by altering water distribution between soil evaporation and plant transpiration (Raeini and Barathakur, 1997). Adoption of surface and sub-surface drip irrigation system along with plastic mulch, save irrigation water by 15-51 and 7-29%, respectively with 11–80% more tomato fruit yield compared to the conventional irrigation system (Zotarelli *et al.*, 2009).

#### **1.4. Model Choosing for Growth and Yield Prediction**

Mathematical simulation of crop growth and yield was initiated about 30 years ago (De Wilt, 1965; De Wilt *et al.*, 1978; and Ducan *et al.*, 1967). Several models have been developed during the last two decades to simulate the growth and development a tomato crop, but only few of them simulate growth, development, and yield (Cooman and Schrevens, 2006). DSSAT software package contains one of the few models that have been used for the simulation of tomato growth, development, and yield under open field conditions (Rinaldi *et al.*, 2007).

##### **1.4.1. DSSAT (Decision Support System for Agrotechnology Transfer)**

It is a collection of independent programs that operate together, and Cropping System Models (CSM) are at its center (Fig 1). It incorporates models for more than 18 different crops (i.e. CERES, CROPGRO, CROPSIM, SUBSTOR, and CENTURY) with software that facilitates the evaluation and application of the crop models for different purposes (Hoogenboom *et al.*, 2003). It's comprehensive software that includes crop models and programs for research applications of those models. Software helps users prepare these databases and compare simulated results with observations to give them confidence in the models or to determine if modifications are needed to improve accuracy (Uehara, 1989; Jones *et al.*, 1998). The programs are used to create databases on crop experiments (including crop management treatments as well as measurements made on soil and crop in the experiments), on soil parameters, and on climatic data. The models predict changes in yield and determine suitable time for cultivation mathematically using



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interaction between different inputs because this model enables us to ask "what if?" questions (ICASA, 2010).

This software package was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT, 1993). The motivation was the need to integrate knowledge about soil, climate, crops, and management for making better decisions about transferring production technology from one location to others where soils and climate differed (Uehara, 1998; and Tsuji, 1998).

It has been in use for the last 20 years by different agricultural research sectors worldwide. It was first released (v2.1) in 1989; additional releases were made in 1994 (v3.0) (Tsuji *et al.*, 1994), 1998 (v3.5) (Hoogenboom *et al.*, 1999) and in 1999 (v4.0) (Hoogenboom *et al.*, 2003). In this study we have used DSSAT v4.5 (Hoogenboom *et al.*, 2009), which is going to be released in fall 2010. One major reason for this re-design is that each individual crop model in DSSAT v3.5 (Figure 1) had its own soil model components (Jones *et al.*, 2003). The main changes have been achieved through releasing different versions were to make the software MS-Windows-based instead of MS-DOS, to include models for other crops that weren't tested before, in addition to improve sensitivity and accuracy of some models and options already existed in the software package. Those redesigning and programming were to facilitate more efficient incorporation of new scientific advances, applications, documentation and maintenance (Jones *et al.*, 2003).

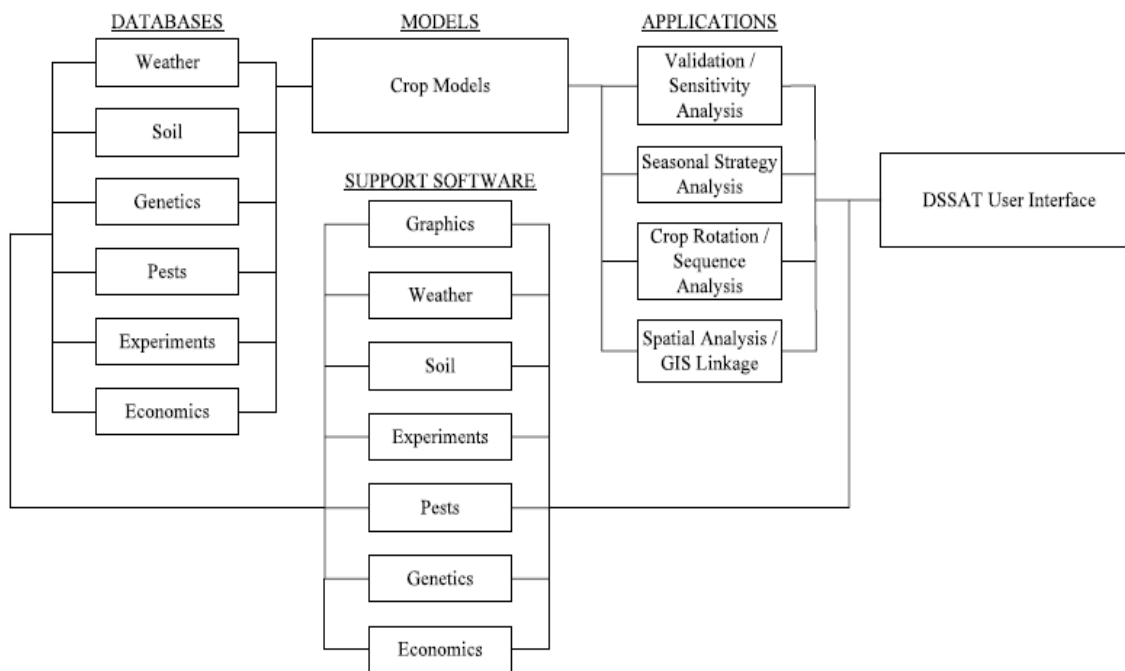


Figure 1. Diagram of database, application, and support software components and their use with crop models for applications in DSSAT v3.5 (Jones *et al.*, 2003).

Several applications of DSSAT software package have been stated in order to expand its uses range. Kelly *et al.* 2008 have studied a methodology to use a prototype decision support system (DSS) called Apollo to manage running the DSSAT models to simulate and analyze spatially variable land and management.

#### 1.4.2. DSSAT Cropping System Model (CSM)

The DSSAT-CSM design is a modular structure in which components separate along scientific discipline lines and are structured to allow easy replacement or addition of modules (Jones *et al.*, 2003). It has a main driver program, a land unit module, and modules for the primary components that make up a land unit in a cropping system (Figure 2).

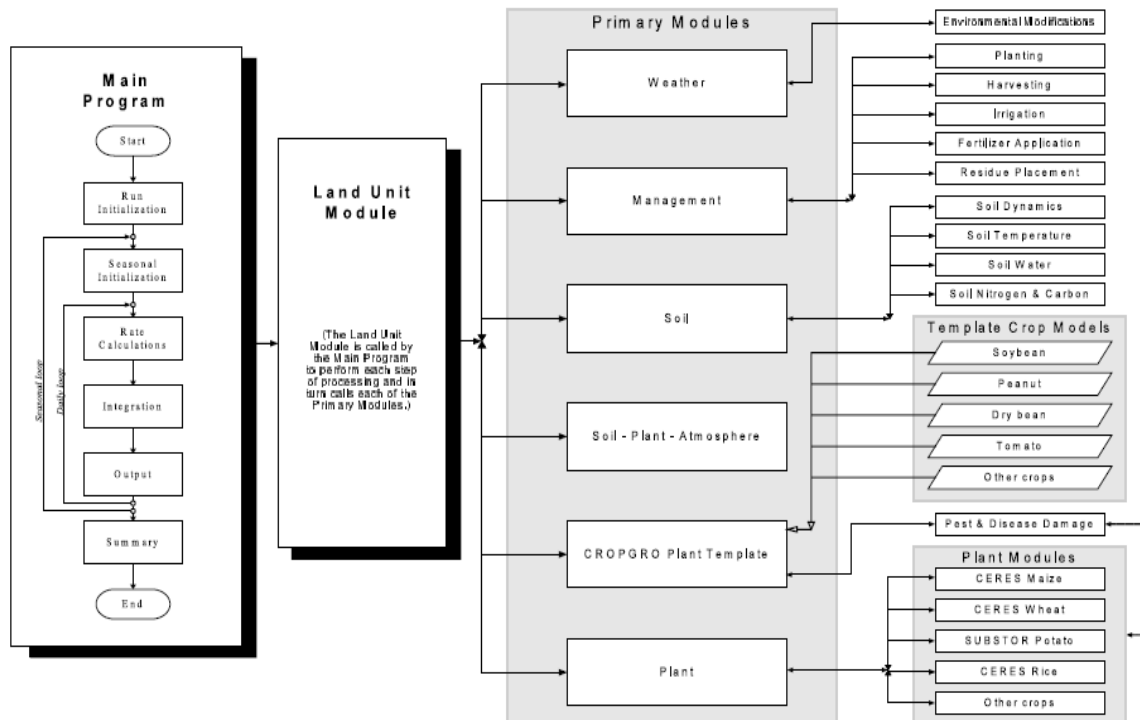


Figure.2. Overview of the components and modular structure of the DSSAT-CSM (Jones *et al.*, 2003).

DSSAT-CSM includes separated modules along disciplinary lines which enables individual components to be plugged in or unplugged with little impact on the main program or other modules. The module in the model structure could be integrated into different application packages and could integrate other components, such as livestock and intercropping, due to the well defined interface to the modules (Jones *et al.* 2001; Jones *et al.*, 2003). The development of such model is made by the modification of these modules in order to achieve several functions such as:

1. Phenology,
2. Soil water balance,
3. Pest damage,
4. Photosynthesis,
5. Crop growth and partitioning,
6. Weather,
7. Soil nitrogen.

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### 1.4.3. CSM-CROPGRO

It's a generic model that computes crop growth processes including phenology, photosynthesis, plant nitrogen and carbon demand, growth partitioning, and pest and disease damage for crops modeled using the CROPGRO model crop template (soybean, peanut, dry bean, chickpea, cowpea, faba bean, tomato, macuna, brachiaria, bahiagrass, etc.). It allows the simulation of plant growth over a wide range of field crops and production systems (Scholberg *et al.*, 1997). CROPGRO was created after the earlier experience in adapting SOYGRO to PNUTGRO and BEANGRO (Hoogenboom *et al.*, 1994) having the idea of one common program with values from files providing information for each species to be modelled. Currently, it simulates ten crops; including seven grain legumes (soybean (*Glycine max* L. Merr.); peanut (*Arachis hypogaea* L.); dry bean (*Phaseolus vulgaris* L.); chickpea; cowpea; velvet bean and faba bean (*Vicia faba* L.), and non-legumes such as tomato (*Lycopersicon esculentum* Mill.) (Scholberg *et al.*, 1997; Boote *et al.*, 1998a,b).

The CROPGRO model is more accepted in the modelling and agricultural research community due to its useful features (Scholberg *et al.*, 1997). Its features are user-friendly interfaces and graphics output, the use of standardised input files, the quality of its documentation, and the linking of the growth routine to both water and nutrient balances (Hoogenboom *et al.*, 1992).

Each module in CSM-CROPGRO model consists of two or more of the following stages, respectively (Figure 3):

1. Input is a stage to call data from CROPGRO data files, this data could be handled between different modules without necessity to pass through the main program, in order to reduce the number of arguments passed to and from it.
2. Initialization is a stage to initialize each variable at the beginning of each simulation season.
3. Rate calculation is a stage at the beginning of the daily time step loop to ensure that change rates of state variables for a given day of simulation are all based on values of these state variables for a common point in time.

4. Integration is a stage updates state variables throughout the model for each day of simulation using the values calculated in the Rate Calculations stage of the module. Daily output is written to files at the end of this stage.
5. Output is a stage where seasonal summary of data is written to output files.
6. Final stage is a section of processing is used to write and of simulations summary output files and to close output files.

The module is handled as a separate unit, so this make the development in such model easy to achieve. The development could be accomplished through any of the above mentioned stages.

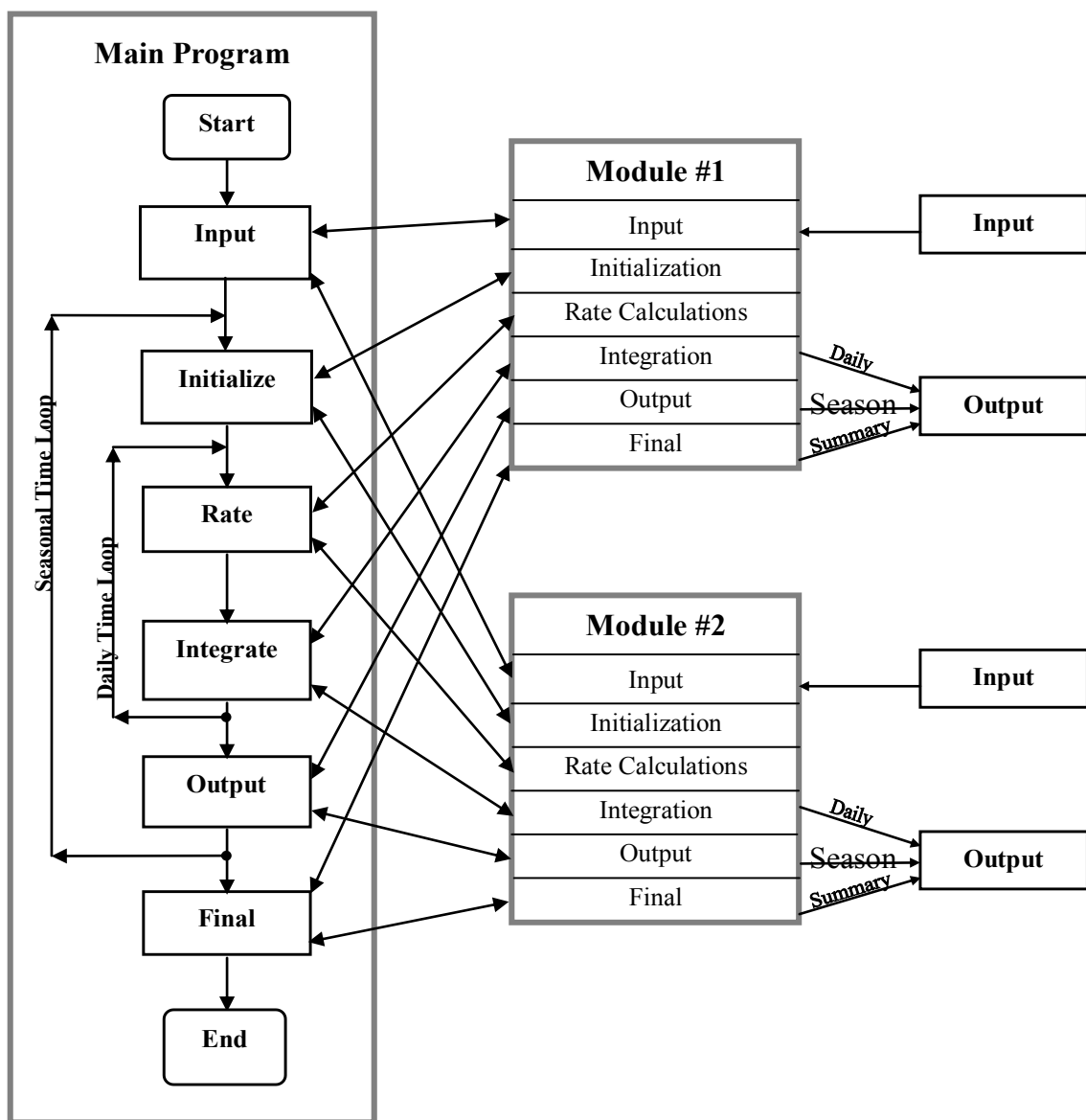


Figure 3. Module Structure (Porter and Jones, 1998)

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#### **1.4.4. CSM-CROPGRO-Tomato**

A number of models have been developed for tomato in order to predict different growth and production parameters (Wolf *et al.*, 1986; Bertin and Heuvelink 1993; and Jones *et al.*, 1989). Jones *et al.* (1991) have developed TOMGRO growth model for greenhouse tomato, but Scholberg *et al.* (1995) found that TOMGRO didn't adequately describe the growth of field-grown tomato. Subsequently, Scholberg *et al.* (1997) have adapted the CROPGRO-Peanut model establishing CROPGRO-Tomato model in order to simulate growth, yield and yield components of the field-grown tomato. Modelling the growth of field-grown tomato (*Lycopersicon esculentum* Mill.) should assist growers and extension workers throughout the world to outline optimal crop management strategies for specific locations and protection systems (Scholberg *et al.*, 1997).

We studied processing tomato production under open field conditions in order to evaluate the CSM-CROPGRO-tomato model and to estimate its potential to simulate tomato production for environmental conditions in northern Italy.

The reason of establishing the study under open field conditions is to consider interaction of different weather elements as this interaction has effect on the influence level of each climate element on the plant. In addition to that, we need to see the influence of photosynthesis and evapotranspiration rate as physiological growth parameters on quality and quantity of tomato yield using CSM simulations. These models need available inputs (for local conditions) and calculate values/rates of photosynthesis and evapotranspiration, and then we have the outputs/results.

#### **1.4.5. Model Calibration, validation, and evaluation**

Before using a crop model for a particular production region, it is important that a minimum amount of crop growth and performance data be collected to allow evaluating model performance for that region's cultivar types, and in some cases for calibration of specific parameters (Hoogenboom *et al.*, 1999).

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## 1.5. Climate Change

### 1.5.1. Motivations to study climate change

The croplands, pastures and forests that occupy 60% of the continent's surface are progressively being exposed to threats from increased climatic variability and, in the longer run, to climate change. (FAO, 2007). In spite of the technological innovation, weather and climate still represent key factors for agriculture productivity so that their impact on primary sector is significant (Vento *et al.*, 2002).

Easterling *et al.* (2007) indicated that several uncertainties about future climate change impacts remain unresolved, so better knowledge in several research areas is critical to improve our ability to predict the magnitude, and often even the direction, of future climate change impacts on crops, as well as to better define risk thresholds and the potential for surprises, at local, regional and global scales.

Recent studies confirm that the effects of elevated CO<sub>2</sub> on plant growth and yield will depend on photosynthetic pathway, species, growth stage and management regime, such as water and nitrogen (N) applications (Jablonski *et al.*, 2002; Kimball *et al.*, 2002; Norby *et al.*, 2003; Ainsworth and Long, 2005). Many recent studies confirm that temperature and precipitation changes in future decades will modify, and often limit, direct CO<sub>2</sub> effects on plants; and increased temperatures may also reduce CO<sub>2</sub> effects indirectly, by increasing water demand (Easterling *et al.*, 2007). Changes in precipitation and, especially, in evaporation-precipitation ratios modify ecosystem function, particularly in marginal areas. Higher water-use efficiency and greater root densities under elevated CO<sub>2</sub> in field and forestry systems may, in some cases, alleviate drought pressures, yet their large-scale implications are not well understood (Schäfer *et al.*, 2002; Wullschleger *et al.*, 2002; Norby *et al.*, 2004; Centritto, 2005).

The IPCC- Third Assessment Report (TAR) indicated that impacts on food systems at the global scale might be small overall in the first half of the 21st century, but progressively negative after that. Importantly, crop production in (mainly low latitude) developing countries would suffer more, and earlier, than in (mainly mid- to high-latitude) developed countries, due to a combination of adverse agro-climatic, socio-economic and technological conditions (Alexandratos, 2005).

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### **1.5.2. Vulnerability of agriculture to climate change**

Arid climate conditions will cause a great supplying problem with increasing water demand and drought for agriculture and forest systems. Agricultural systems are more vulnerable to climate changes than other systems especially in arid and semi arid regions. The considerable efforts needed to prepare for climate-related impacts and the time required for agriculture and forestry production systems to adapt is the crucial point (FAO, 2007). Sustainable agriculture can benefit both the environment and food production (IPCC, 2001).

The effect of climate change factors on tomato crop is an essential field of study as it is an important crop involved in food enriching programs of numerous regions. There is a need for more research in the Mediterranean region under future environmental pressures. More researches are needed taking into consideration the socioeconomic adaptation of this crop for climate change and other related stresses.

Smallholder and subsistence farmers, pastoralists and artisanal fisherfolk whose adaptive capacity is constrained, will experience the negative effects on yields of low-latitude crops, combined with a high vulnerability to extreme events. In the longer term, there will be additional negative impacts of other climate-related processes such as snow-pack decrease (especially in the Indo-Gangetic Plain), sea level rise, and spread in prevalence of human diseases affecting agricultural labour supply (Easterling *et al.*, 2007).

### **1.5.3. Adaptation options to eliminate global warming effects**

There are multiple adaptation options that imply different costs, ranging from changing practices in place to changing location of agricultural activities, and its effectiveness varies from only reducing negative impacts to changing a negative impact into a positive one (Easterling *et al.*, 2007).

IPCC-Fourth Assessment Report (FAR) reported that many of the autonomous adaptation options identified before and since the TAR are largely extensions or intensifications of existing risk-management or production-enhancement activities. For cropping systems there are many potential ways to alter management to deal with projected climatic and atmospheric changes (Aggarwal and Mall, 2002; Alexandrov *et al.*, 2002; Tubiello *et al.*, 2002; Adams *et al.*, 2003; Easterling *et al.*, 2003; Howden *et al.*, 2003;



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Howden and Jones, 2004; Butt *et al.*, 2005; Travasso *et al.*, 2006; Challinor *et al.*, 2007). These adaptations include:

- altering inputs such as varieties and/or species to those with more appropriate thermal time and verbalization requirements and/or with increased resistance to heat shock and drought, altering fertiliser rates to maintain grain or fruit quality consistent with the climate and altering amounts and timing of irrigation and other water management practices;
- wider use of technologies to ‘harvest’ water, conserve soil moisture (e.g., crop residue retention) and to use water more effectively in areas with rainfall decreases;
- water management to prevent waterlogging, erosion and nutrient leaching in areas with rainfall increases;
- altering the timing or location of cropping activities;
- diversifying income by integrating other farming activities such as livestock raising;
- improving the effectiveness of pest, disease and weed management practices through wider use of integrated pest and pathogen management, development and use of varieties and species resistant to pests and diseases, maintaining or improving quarantine capabilities, and sentinel monitoring programs;
- using seasonal climate forecasting to reduce production risk.

### **1.6. Applying meteorology to agriculture through crop models**

For a crop model to be useful as a climate change impact assessment tool, it has to reliably predict yield as a function of weather variables and have a relatively limited number of essential variables and parameters - models developed to express understanding derived directly from research are not particularly suited to practical application where limited data might be available for parameterization, calibration and testing. It must also be available to users in a robust yet flexible package that readily facilitates implementation, have a CO<sub>2</sub> response equation in the simulation, and operate at suitable spatial and temporal scales (WMO, 2010).

A review of literature for regional studies using the CROPGRO model (for a review of the model, see Hoogenboom *et al.*, 1992), the CERES model (a user manual is provided by Goodwin *et al.*, 1990) and the SUBSTOR model (described by Singh *et al.*, 1998)

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reveals a predominance of work conducted for more developed countries (perhaps because the necessary data of suitable quality are available for these regions). The impact assessments focus mainly on the effects of elevated CO<sub>2</sub>, temperature, precipitation and radiation on yield, but some authors have examined how these factors influence crop suitability and changing spatial distributions of crops (for instance, Iglesias *et al.*, 2000; Rosenzweig *et al.*, 2002; Jones and Thornton, 2003). While workers tend to conclude that increases in yield are likely, they discuss issues of importance such as timing of water in Indian monsoon, which can cause reduced yield (Lal *et al.*, 1998, 1999), and the uncertainty of the yield forecasts (soybean and peanut yield increases, maize and wheat yield decreases) in the south-eastern United States (Alexandrov and Hoogenboom, 2004). The potential effect of the daytime vs. night-time rise in temperature is discussed by Dhakhwa *et al.* (1997), who suggest that an asymmetrical change, with greater change at night-time, would have less impact on yield than a symmetrical change. Another important issue is the potential significance of cultivar selection (Alexandrov *et al.*, 2002; Kapetanaki and Rosenzweig, 1997). There have been studies for Africa and other developing regions (for example, Jones and Thornton, 2003), but authors recognize that a model to predict yield changes is unlikely to capture the true impact of climate change on smallholders and non-mechanized farmers in these regions.

## **Objectives**

- Assessment of crop growth and yield of processing tomato local varieties at different transplanting dates under open field conditions
- Evaluating the Cropping System Model (CSM)-CROPGRO-Tomato of DSSAT (Decision Support System for Agrotechnology Transfer) software with experimental datasets obtained from field experiments that were conducted in Legnaro, northern Italy in 2009.
- Validating CSM-CROPGRO-Tomato model using the experimental datasets of 2010.
- Estimating future processing tomato plant growth and yield by applying CSM-CROPGRO-Tomato model using two different future climate scenarios.

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**Chapter 2**

**Influence of Different Planting Dates on Growth, Yield,  
and Yield Components of Processing Tomato Varieties  
under Open Field Conditions**

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## **2.1. Introduction**

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According to FAO the top six producers of tomatoes in 2009 were China, United States, India, Turkey, Egypt, and Italy, respectively, whereas the annual production in 2009 in the Mediterranean was more than 29.9 million tons, which represents about 21% of the global production (FAO, 2009).

Italy produces more than 6.4 million tons of tomatoes annually from an area of 117100 ha at an average yield of 54506.4 kg ha<sup>-1</sup> (FAO, 2009). This represents 21.4% of Mediterranean production and about 5% of the global production. Italy dominates the global processed tomato products market (FAO, 2007). The World Processing Tomato Council stated in 2006 that Italy supplied 18% of the total world production in 2005 for processing tomato, and northern Italy produce more than 40% of Italy's total production (AMITOM, 2006).

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## **2.2. Materials and Methods**

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### **2.2.1. Nursery Conditions**

Four processing tomato varieties were obtained from two local seed companies in order to be used in 2009: Augusto F1 (AUG) and Tiziano F1 (TIZ) were obtained from De Ruitter company; and NPT 63 (NPT) and Safaix (SAF) from S&G company. For 2010, AUG and NPT varieties were chosen among the four varieties tested in 2009 year just to confirm the results obtained and having the best variety (NPT) and one among the other three (AUG).

The seeds were sown in foam trays containing 336 holes (hole dimension was 2x2 cm<sup>2</sup>). The growing media used to grow the seeds was peat moss growing media. Sowing the seeds into the holes was manually using clamps. The sown trays were covered by a layer of vermiculite then with a white net till germination starting. Trays were placed in a warm metal-glass greenhouse. They were transferred to a cool plastic greenhouse when plantlets having 2-3 true leaves.

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Four sowing dates were applied with ten-days interval starting from 11<sup>th</sup> March in 2009 and from 23<sup>rd</sup> March. In 2010. Medium of temperature inside the greenhouse during the nursery period was 20.5 °C. Irrigation during that period was manual sprinkling irrigation. It has been applied till obtaining two true leaves, then the fertigation (Pimpini *et al.*, 2004) was applied alternatively with irrigation. Amount of macro and micro elements and water used to prepare nutrient solution for fertigation are shown in table 1.

### **2.2.2. Site & Field Management**

After growing the plantlets under nursery conditions for 40 days, they were transplanted in the open field with 10 days interval between the four transplanting dates (TD1, 2, 3, and 4). The location of that field was Agripolis, L. Toniolo (45° 21' N; 11° 58' E), Veneto region, northeastern Italy. The open field experiments started on 14<sup>th</sup> April 2009 and finished on 2<sup>nd</sup> September 2009 and on 29<sup>th</sup> April 2010 and finished on 30<sup>th</sup> August 2010.

The drip irrigation net was fixed few days before the transplanting. Each irrigation line for each plot was attached with a water gauge in order to measure the amount of water released at each applied irrigation.

Phosphorus and potassium fertilizers were applied also few days before the transplanting, whereas nitrogen fertilizer was applied immediately before the time of transplanting for each transplanting date. Amounts and forms of fertilizers applied are displayed in table 2 and 3. For mulched plots, nitrogen fertilizer was applied once at the beginning of the experiment, whereas the same amount for non-mulched plots was divided into two dozes in 2009 and into three dozes in 2010.

Table 1: Macro and micro elements used to prepare the nutrient solution for nursery fertigation (Pimpini *et al.*, 2004).

<b>EC</b>	<b>mS cm<sup>-1</sup></b>	<b>2.3</b>	
<b>pH</b>		<b>5.5-6.2</b>	
<b>Element type</b>	<b>Element name</b>	<b>ppm</b>	<b>g in 25l H<sub>2</sub>O</b>
<b>Macro elements</b>	Ca(NO <sub>3</sub> ) <sub>2</sub>	918.4	22.9606
	NH <sub>4</sub> H <sub>2</sub> PO <sub>4</sub>	46.0	1.1500
	KH <sub>2</sub> PO <sub>4</sub>	115.7	2.8921
	K <sub>2</sub> SO <sub>4</sub>	305.0	7.6256
	MgSO <sub>4</sub>	492.6	12.3150
	KNO <sub>3</sub>	444.4	11.1100
<b>Micro elements</b>	MnSO <sub>4</sub> xH <sub>2</sub> O	0.55	0.0423
	ZnSO <sub>4</sub> x7H <sub>2</sub> O	0.33	0.0359
	CuSO <sub>4</sub> x5H <sub>2</sub> O	0.05	0.0047
	H <sub>3</sub> BO <sub>3</sub>	0.32	0.0464
	K <sub>2</sub> MoO <sub>4</sub>	0.05	0.0030
	Iron	0.84	0.1376

Soil was ploughed and divided into plots according to the split-split plot design (Figure 4.1, 4.2). Soil of mulched plots was mulched using a black poly-ethylene plastic film.



Table 2: Fertilization applied for the open field experiments in 2009.

Type of fertilizer	Fertilizer form	Amount (kg ha <sup>-1</sup> )	Time of application for mulched plots	Time of application for non-mulched plots
Nitrogen	N (Urea)	150	At date of transplanting	½ at date of transplanting, and ½ at one month of transplanting
Phosphorus	P <sub>2</sub> O <sub>5</sub> (Super phosphate)	150	Few days before transplanting	Few days before transplanting
Potassium	K <sub>2</sub> O (Potassium sulfate)	200	Few days before transplanting	Few days before transplanting

Table 3: Fertilization applied for the open field experiments in 2010.

Type of fertilizer	Fertilizer form	Amount (kg ha <sup>-1</sup> )	Time of application for mulched plots	Time of application for non-mulched plots
Nitrogen	N (Urea)	150	At date of transplanting	1/3 at date of transplanting, 1/3 at one month of transplanting, and 1/3 at two months of transplanting
Phosphorus	P <sub>2</sub> O <sub>5</sub> (Super phosphate)	100	Few days before transplanting	Few days before transplanting
Potassium	K <sub>2</sub> O (Potassium sulfate)	120	Few days before transplanting	Few days before transplanting

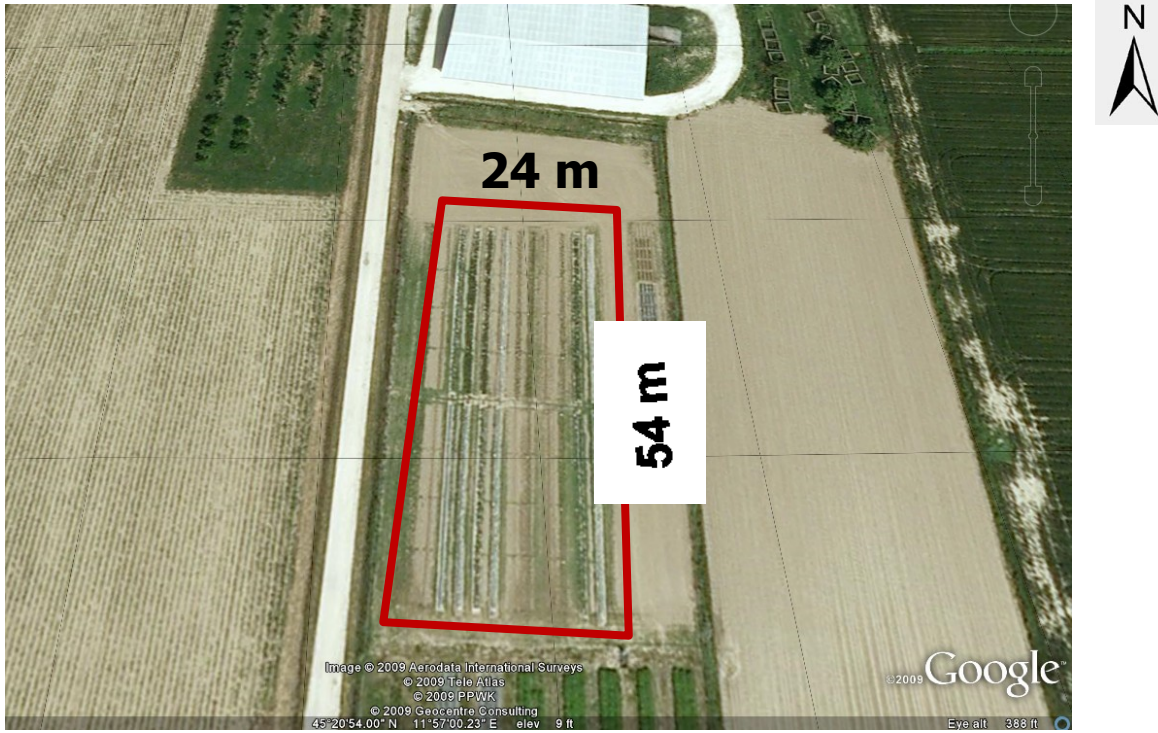


Figure 4.1: Pilot view of the site used for the open field experiment in 2009

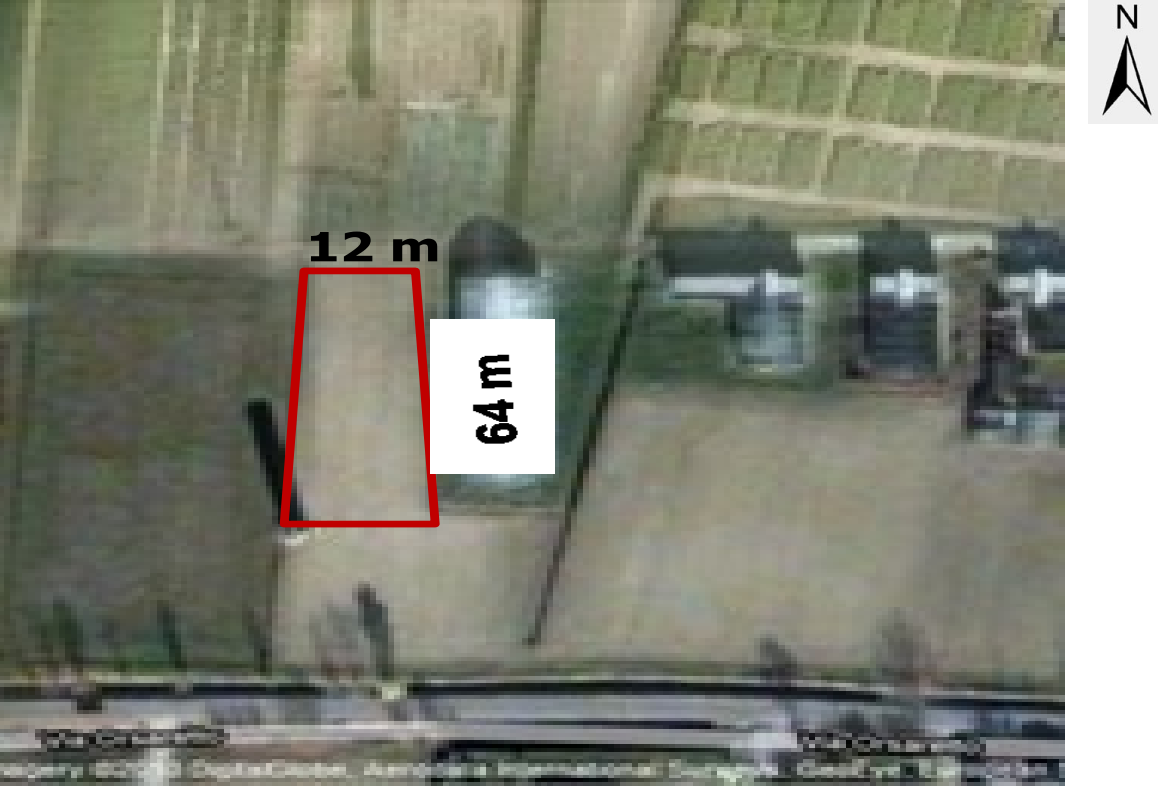


Figure 4.2: Pilot view of the site used for the open field experiment in 2010

### 2.1.1. Experimental design

An area of 1169 m<sup>2</sup> in 2009 and of 768 m<sup>2</sup> in 2010 was ploughed and divided according to a split-split plot design as shown in Figure 5 and 6. The experiment was consisted of three replicates (three blocks). The main factor was mulching the soil, which was applied for half of each block. The transplanting dates were the sub-plots and the varieties were sub-sub-plots. Regarding the planting distances, the inter-row distance was 40 cm and the in-row distance was 30 cm. these distances were used according to the industrial field grown tomato practices in the region under study.

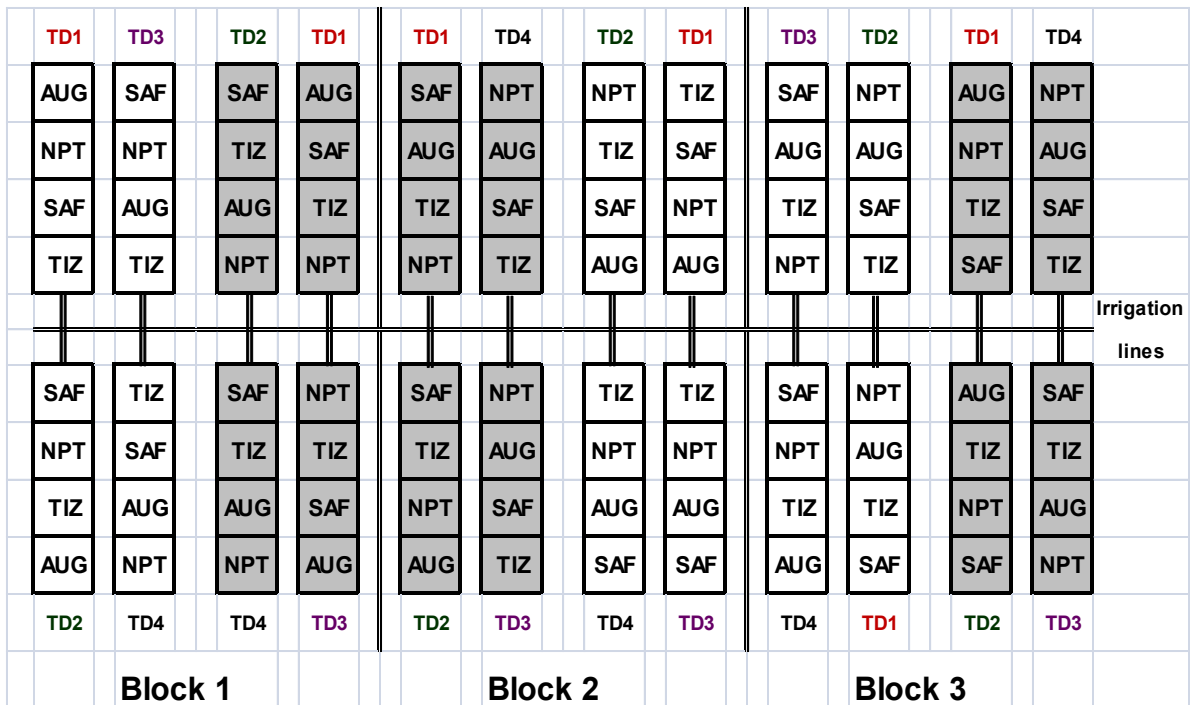


Figure 5: Open field experimental design (split-split plot) in 2009

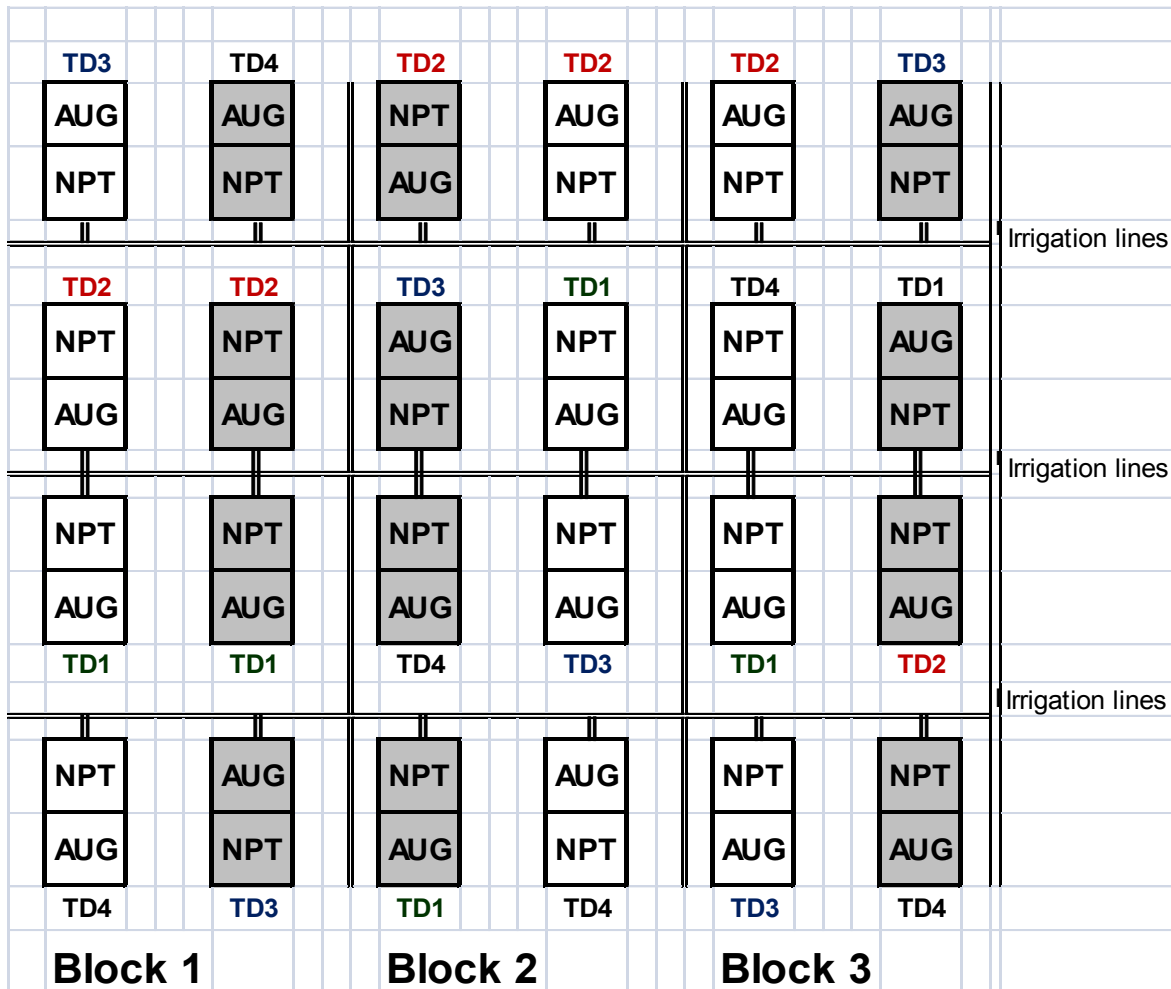


Figure 6: Open field experimental design (split-split plot) in 2010.

### 2.1.2. Parameters

The parameters that were collected included:

- (1) Daily meteorological observations included maximum and minimum temperature ( $^{\circ}\text{C}$ ), precipitation (mm), and total solar radiation ( $\text{MJ m}^{-2}$ ).
- (2) Soil physical and chemical characteristics, included chemical (pH in water, EC in water, total N, nitrate, ammonium and total organic carbon) and physical (soil texture, bulk density, and CEC) characteristics.
- (3) Vegetative growth and development included: fresh and dry biomass  $\text{plant}^{-1}$  (kg), vegetative part (leaves + stems) fresh and dry weight  $\text{plant}^{-1}$ , leaf area  $\text{plant}^{-1}$  ( $\text{m}^2$ ), number of leaves  $\text{plant}^{-1}$ , canopy height (m), fresh and dry fruit weight  $\text{plant}^{-1}$  (kg), and number of fruits  $\text{m}^{-2}$ .

(4) Yield, included fresh and dry biomass plant<sup>-1</sup> (kg), fresh and dry fruit weight plant<sup>-1</sup> (kg), and total number of fruits m<sup>-2</sup>.

Sample intervals and main operations in the two soil management treatments can be summarised as illustrated in figure 7. These measurements were obtained according to the minimum datasets required to be able to run and evaluate crop models (Hunt *et al.*, 2001).

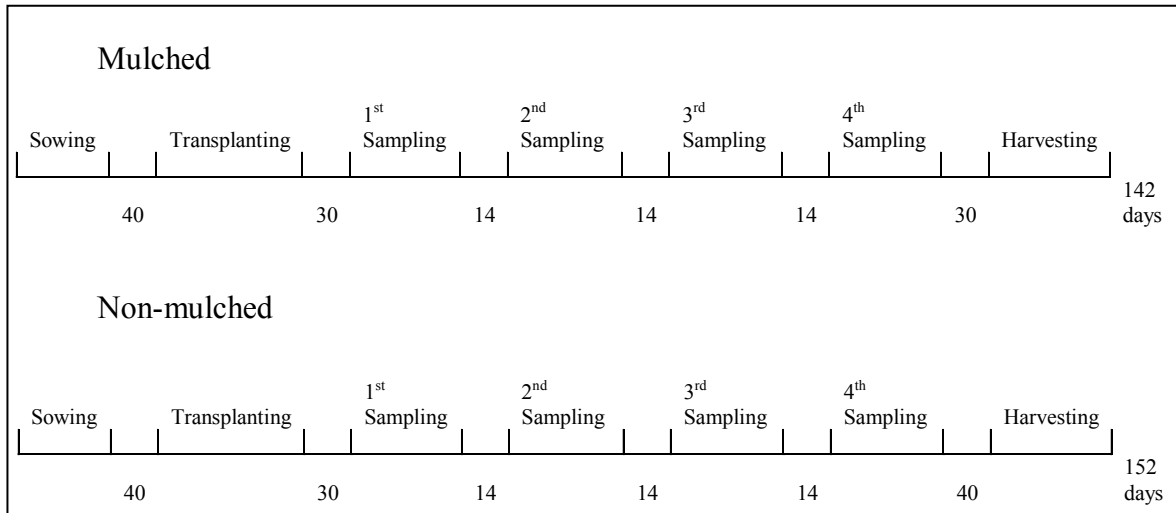


Figure 7: Representation of the structure of sampling for the two treatments (mulched vs. non-mulched).

### 2.1.3. Statistical analysis

Data for vegetative growth, dry matter content and yield were analysed statistically using Duncan test (Statgraphics program) at 0.05 probabilities.

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## 2.3. Results and Discussion

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### 2.3.1. SPAD measurement

Comparing SPAD values, which represents the chlorophyll content of plant leaves, the plants in 2009 showed that the values in general ranged between 40 and 70 during the growing cycle. For TD1 under both mulched and non-mulched conditions, SPAD evolution was better for TIZ variety, then almost the same levels for SAF and AUG varieties, whereas NPT had the lowest levels. For TD2, under mulched conditions the difference among varieties was almost similar to TD1, whereas under non-mulched conditions TIZ was always better than the other three varieties. For TD3 and TD4 under both mulched and non-mulched conditions, SPAD levels in all varieties were similar to TD1 (Figure 8).

TIZ showed better SPAD levels than the other three varieties with values ranged between 55 and 67 in all transplanting dates, which is proved due to variety characteristics. There wasn't a great effect of mulched and non-mulched conditions on levels and evolution of SPAD at all transplanting dates. For TD1 and TD2, SPAD levels were relatively lower than those for TD3 and TD4, which could be due to higher temperature and global solar radiation at late transplanting dates.

Comparing the two processing tomato varieties in 2010 under different conditions we found that AUG variety (ranged between 54 and 65) gave better SPAD values than NPT variety (ranged between 45 and 59). Under mulched conditions, the changes in SPAD values through growing cycle were slow and maintained, whereas under non-mulched conditions, the decline in SPAD was fast (Figure 9).

These changes during the growing cycle were due to forcing the growth towards fruit production and decrease or slow down the vegetative growth. The differences in SPAD values between the two varieties could be explained as NPT gave vigour growth and AUG gave lower growth level, so under same environmental and nutritional conditions, plants of AUG recovered the shortage in growth through increasing chlorophyll contents in leaves.

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### 2.3.2. Final Yield

The comparison of plant behaviour in 2009 with or without mulching showed that mulching the soil significantly enhanced yield of all varieties under study giving 70.70 t ha<sup>-1</sup> fresh weight and 3.11 t ha<sup>-1</sup> dry weight using mulch and 37.91 t ha<sup>-1</sup> fresh weight and 1.68 t ha<sup>-1</sup> dry weight without using it (Table 3). This effect of mulching the soil could be due to the increased soil water retention and soil temperature at the plant root zone, which ameliorate root growth development but mainly on protecting the plant from weeds competition. Comparing yield of the four different tomato varieties we can see that NPT had significantly the best performance (65.86 t ha<sup>-1</sup> fresh and 2.90 t ha<sup>-1</sup> dry) followed by TIZ (53.01 t ha<sup>-1</sup> and 2.34 t ha<sup>-1</sup> dry), AUG (49.18 t ha<sup>-1</sup> and 2.17 t ha<sup>-1</sup> dry), and SAF (49.16 t ha<sup>-1</sup> and 2.18 t ha<sup>-1</sup> dry), respectively. This was due to different genetic characteristics of each variety which gave vigour vegetative growth for NPT variety compared with the other three varieties. There were no significant differences between yield obtained from all varieties transplanted at different transplanting dates in both fresh and dry matter, which indicate that changing transplanting date in the range considered (from April 14 to May 25, 2009) didn't reflect different weather conditions on the plants were exposed to.

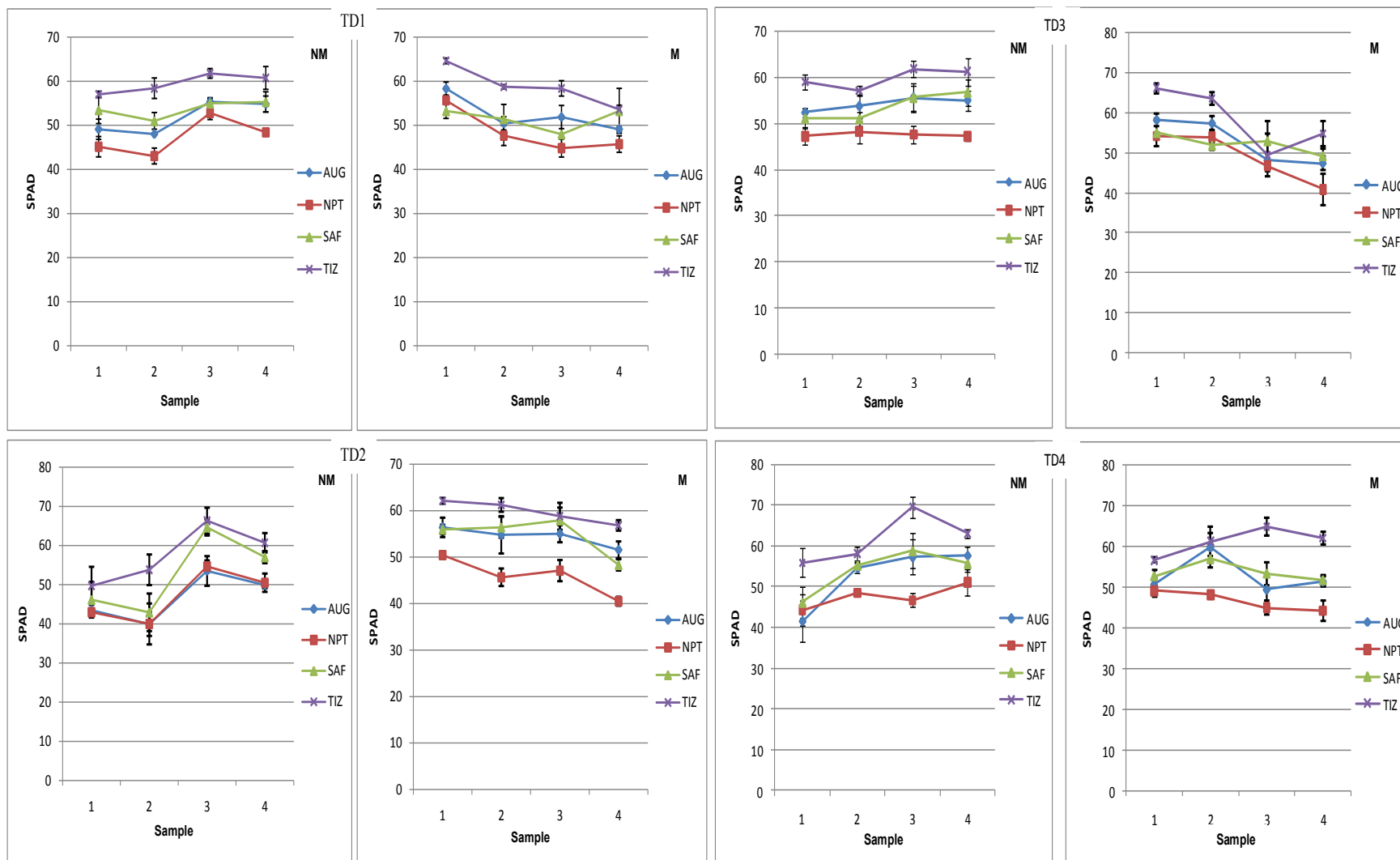


Figure 8: SPAD values of the four different processing tomato varieties during the growing cycle under (a) non-mulched and (b) mulched soil conditions in 2009



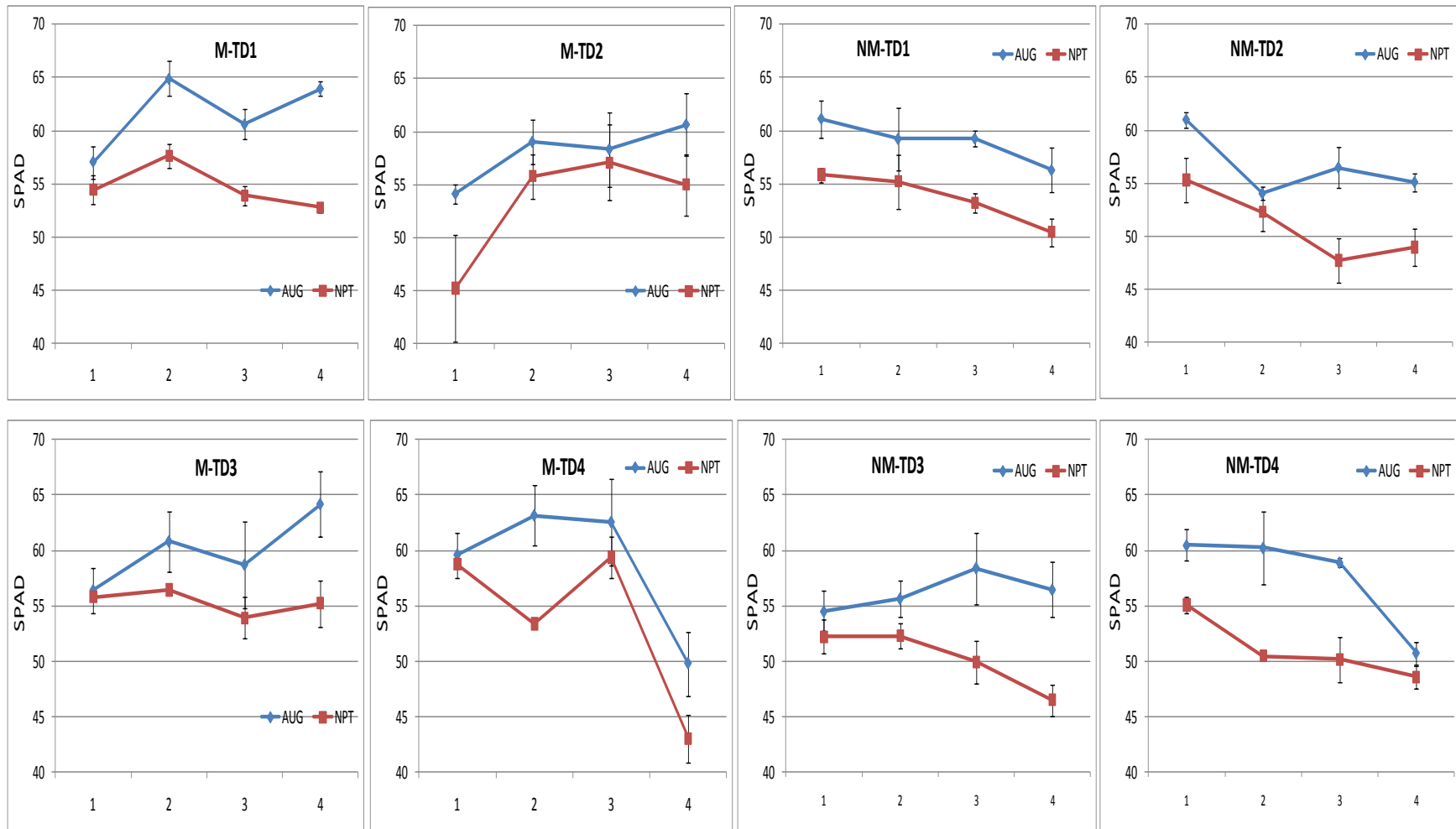


Figure 9: SPAD values of the four different processing tomato varieties during the growing cycle under (a) non-mulched and (b) mulched soil conditions in 2010

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In 2010, the yield under both mulched and non-mulched soil conditions didn't vary significantly in both fresh and dry weight. Comparing fresh yield at different transplanting dates, there were no significant differences among them, whereas the dry weight varied significantly giving better yield at TD1 (8.48 t ha<sup>-1</sup>), TD2 (6.74 t ha<sup>-1</sup>), TD3 (5.05 t ha<sup>-1</sup>) more than TD4 (2.99 t ha<sup>-1</sup>). That indicates anticipation of transplanting date has a positive effect on plant growth, development and yield consequently. For the comparison between AUG and NPT varieties, There were significantly better fresh and dry yield for NPT variety (123.19 t ha<sup>-1</sup> fresh and 6.69 t ha<sup>-1</sup> dry) than AUG variety (99.37 t ha<sup>-1</sup> fresh and 4.94 t ha<sup>-1</sup> dry). That result confirmed the result of the previous year favouring NPT variety under different conditions. Looking at the interaction between factors affected yield, we can find a significant effect of the combination between mulching and variety. This gave better results for NPT variety under mulching conditions compared with AUG variety under the same conditions, and both of them are better than plants under non-mulched conditions.

The difference between results of the two years was due to different weather conditions. In 2009, the precipitation amounts during growth cycle were 178, 246, 286 and 276 mm from TD1 to TD4, respectively, whereas in 2010 they were 274, 317, 305 and 314 mm from TD1 to TD4, respectively. Precipitation frequency was more in 2010 than in 2009 with an average of 10 days. These differences gave better conditions in 2010 to have better yield. The average temperature in 2009 was between 16 and 20 °C, while in 2010 average temperature was between 20.5 to 22 °C during the growing cycle. Higher temperature in 2010 favour also plant growth, development and yield, consequently.

### **2.3.3. Water use efficiency**

Rinaldi *et al.* (2007) stated that water stress can modify the water use efficiency. Therefore, irrigation amount was taken into consideration in order to evaluate water use efficiency at different transplanting date under study. Figure ? shows in 2009, accordingly with yield results, that under mulched conditions TD1 had the lowest water use efficiency (12.36 t m<sup>-3</sup>) followed by the other three transplanting dates, with no significant differences among them. Significant positive influence for water use efficiency was observed under mulched conditions at all transplanting dates, which could be due to an increase of root expansion under mulched conditions (Rinaldi *et al.*, 2007). This effect could be due to the

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increased soil water retention and soil temperature at plant root zone, which ameliorate root growth development but mainly on protecting the plant from weeds competition.

Rinaldi *et al.* (2007) stated that water stress can reduce the ability of plant roots to absorb maximum nutrients while nitrogen shortage can reduce water use efficiency. Therefore, the total amount of irrigation that was applied was taken into consideration in order to evaluate water use efficiency for each variety. According to the yield results under mulched conditions, in 2010 there were no significant differences observed for water use efficiency among different varieties, whereas TD1 (44 t m<sup>-3</sup>) and TD2 (48 t m<sup>-3</sup>) gave significantly better water use efficiency than late transplanting dates (Figure ?). Under non-mulched conditions, the differences among transplanting dates were not significant. Accordingly, significant influences were observed for water use efficiency between mulched and non-mulched conditions for all the treatments under study.

The difference between water use efficiency in 2009 and 2010 as due to different weather conditions, especially precipitation amount and frequency, which mainly affected plant growth and its efficiency in using water of both irrigation and rainfall.

#### **2.3.4. Water consumption**

In 2009, plants under mulched conditions showed significantly lower water consumption (ranged between 5500 and 3222 m<sup>3</sup> ha<sup>-1</sup>) than those under non-mulched conditions (ranged between 8240 and 5450 m<sup>3</sup> ha<sup>-1</sup>) at different transplanting dates (Figure ?). Under non-mulched conditions, water consumption at TD1 was the highest (8240 m<sup>3</sup> ha<sup>-1</sup>), whereas at TD2, TD3, and TD4 were 7050, 6850, and 5450 m<sup>3</sup> ha<sup>-1</sup>, respectively, with no significant differences between TD2 and TD3. This effect was due to the lower evapotranspiration rate in early transplanting dates as temperature was relatively low.

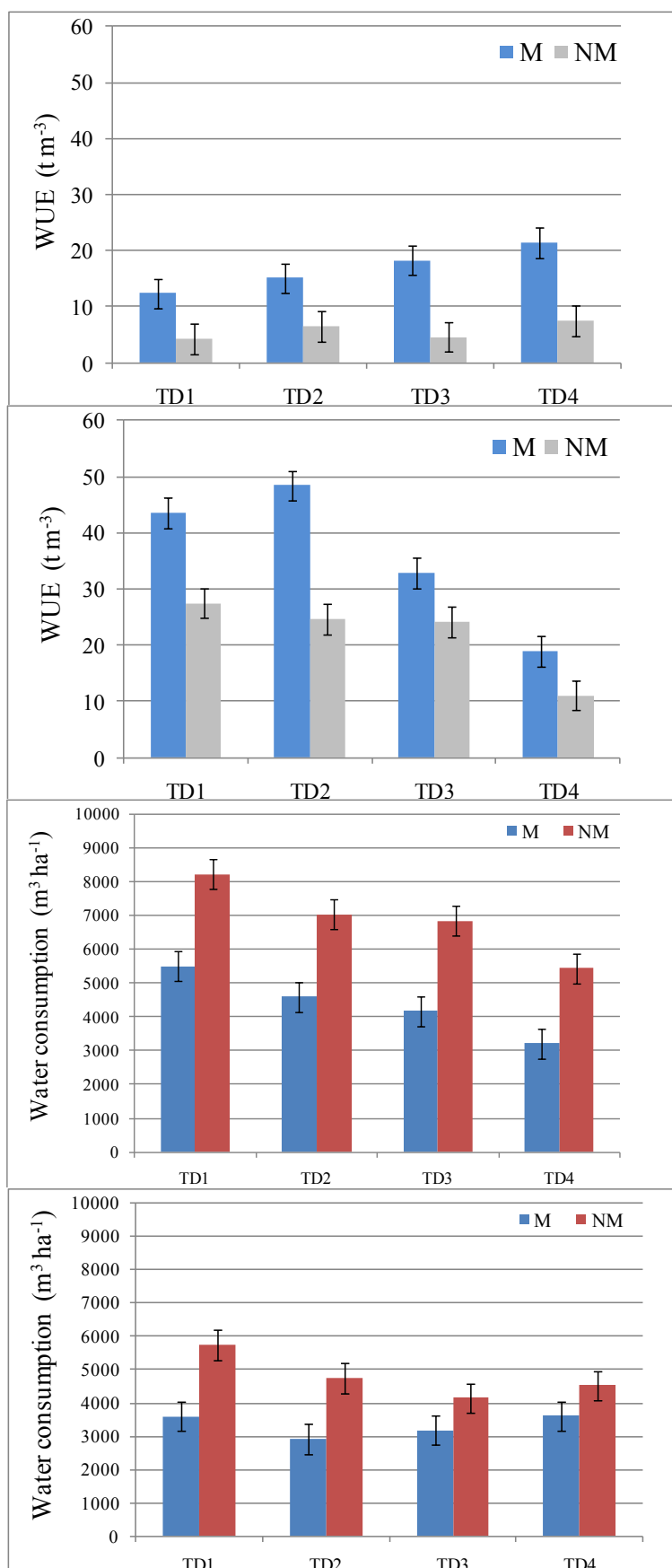


Figure 10: Influence of mulched (M) and non-mulched (NM) treatments on the water use efficiency ( $\text{kg m}^{-3}$ ) of tomato plants at four different transplanting dates in 2009. Vertical bars represent 95.0 % confidence interval.

Figure 11: Influence of mulched (M) and non-mulched (NM) treatments on the water use efficiency ( $\text{kg m}^{-3}$ ) of tomato plants at four different transplanting dates in 2010. Vertical bars represent 95.0 % confidence interval.

Figure 12: Influence of mulched (M) and non-mulched (NM) treatments on the water consumption ( $\text{m}^3$ ) of the four different transplanting dates in 2009. Vertical bars represent 95.0 % confidence interval.

Figure 13: Influence of mulched (M) and non-mulched (NM) treatments on the water consumption ( $\text{m}^3$ ) of the four different transplanting dates in 2010. Vertical bars represent 95.0 % confidence interval.

Table 4: Total fresh and dry weight of tomato plants yield in years 2009 and 2010

Total fruit weight				
	2009		2010	
	FW	DW	FW	DW
t ha <sup>-1</sup>				
<b>Mulch (M)</b>				
Without	37.91 b	1.68 b	106.33	5.25
With	70.70 a	3.11 a	115.60	6.34
<b>Planting (P)</b>				
TD1	51.11	2.31	157.26	8.48 a
TD2	57.36	2.54	126.72	6.74 ab
TD3	53.93	2.35	102.61	5.05 b
TD4	54.81	2.40	59.11	2.99 c
<b>Var (V)</b>				
AUG	49.18 b	2.17 b	99.37 b	4.94 b
NPT	65.86 a	2.90 a	123.19 a	6.69 a
SAF	49.16 b	2.18 b	-	-
TIZ	53.01 b	2.34 b	-	-
<b>Interaction</b>				
MxP	ns	ns	ns	ns
MxV	ns	ns	*	*
PxV	ns	ns	ns	ns
MxPxV	*	*	ns	ns

In 2010, mulching the soil significantly reduced water consumption at all transplanting dates, and there were no significant differences among dates of transplanting (figure 13). Under non-mulched conditions, water consumption at TD1 (5751 m<sup>3</sup> ha<sup>-1</sup>) was significantly higher than the other three transplanting dates.

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### **2.3.5. Total plant fresh weight and dry matter**

In 2009, comparing total plant fresh weight and dry matter under mulching and non-mulching conditions showed that using mulch increased significantly fresh weight (86.6 t ha<sup>-1</sup>) and dry matter (6.3 t ha<sup>-1</sup>) of the plant more than fresh weight (50.8 t ha<sup>-1</sup>) and dry matter (9.5 t ha<sup>-1</sup>) of plants under non-mulched conditions (table 5). The comparison between different transplanting dates showed no significant differences between them for both total plant fresh weight and dry matter (table 5). NPT variety showed significantly better plant fresh weight (81.9 t ha<sup>-1</sup>) and dry matter (5.9 t ha<sup>-1</sup>) followed by TIZ (65.6 fresh and 5.1 dry t ha<sup>-1</sup>), SAF (64.5 t ha<sup>-1</sup> fresh and 5.0 t ha<sup>-1</sup> dry) and AUG (62.9 t ha<sup>-1</sup> fresh and 5.1 t ha<sup>-1</sup> dry), respectively.

In 2010, mulching the soil didn't give a significant effect in total plant fresh weight, while it gave significantly better results for the total plant dry weight (12.9 t ha<sup>-1</sup>) than plants weight from non-mulched plots (9.5 t ha<sup>-1</sup>) (table 5). Comparing the effect of different transplanting dates showed that TD1 (181.7 t ha<sup>-1</sup>), TD2 (152.2 t ha<sup>-1</sup>) and TD3 (127.1 t ha<sup>-1</sup>) gave significantly better total plant fresh weight than TD4 (86.1 t ha<sup>-1</sup>). Total plant dry weight at TD1 (13.4 t ha<sup>-1</sup>) and TD2 (12.4 t ha<sup>-1</sup>) conditions was significantly better results than at TD3 (10.9 t ha<sup>-1</sup>), and TD4 (8.3 t ha<sup>-1</sup>) significantly gave the worst total plant dry weight. NPT variety had significantly better results for both total plant fresh weight (150 t ha<sup>-1</sup>) and dry weight (12.2 t ha<sup>-1</sup>) than AUG variety (122.8 t ha<sup>-1</sup> fresh and 10.0 t ha<sup>-1</sup>). The interaction between mulching and variety effects was significant for both total plant fresh weight and dry weight.

The results of the total plant fresh weight favored the early transplanting dates and NPT variety in order to have better results for location under study. Mulching the soil also improved plant weight due to ameliorating water use efficiency as well as enhancement of nutrients absorption.

### **2.3.6. Vegetative part fresh weight and dry matter**

The comparison between mulched and non-mulched soil treatments in 2009 showed that using mulch significantly improved both fresh weight (15.92 t ha<sup>-1</sup>) and dry matter (3.2 t ha<sup>-1</sup>) of vegetative part of the plant more than without using it (Table 5). Comparing the effect of different transplanting dates, it were observed significant differences between vegetative dry matter giving significantly better results for both TD2 (3.0 t ha<sup>-1</sup>) and TD3

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(3.1 t ha<sup>-1</sup>) more than both TD1 (2.7 t ha<sup>-1</sup>) and TD4 (2.7 t ha<sup>-1</sup>). Comparing varieties showed also that NPT and SAF varieties gave significantly better vegetative fresh weight (16.1 t ha<sup>-1</sup> and 14.8 t ha<sup>-1</sup>) than AUG and TIZ varieties (13.7 t ha<sup>-1</sup> and 12.6 t ha<sup>-1</sup>), respectively. Varieties didn't show significant differences between them for the vegetative dry weight.

In 2010, table 5 is showing that mulching the soil gave significantly better vegetative fresh weight (30.0 t ha<sup>-1</sup>) and dry weight (3.2 t ha<sup>-1</sup>) than plants under non-mulched conditions (21.1 t ha<sup>-1</sup> fresh and 2.5 t ha<sup>-1</sup> dry). Comparing different transplanting dates showed no significant effects among them for both vegetative fresh and dry weight. In addition, there was no significant difference between the two tomato varieties in terms of vegetative fresh and dry weight. The interaction between mulching and variety gave significant difference among different treatments.

### **2.3.7. Number of leaves per plant**

The results in 2009 showed that mulching the soil as well as changing transplanting dates didn't give a significant effect on the n° leaves/plant (table 6). Comparing different varieties under study demonstrated that SAF variety gave significantly better results higher n° leaves/plant (20.33) than the other three varieties, which gave 17.79, 17.35 and 16.09 n° leaves/plant, respectively.

In 2010, table 6 is showing that mulching the soil gave higher n° leaves/plant (10.02) than the plants under non-mulched conditions (9.04). The comparison of different transplanting dates effect on n° leaves/plant showed that there were no significant influence between TD1 (9.38), TD2 (10.95) and TD4 (9.96), whereas TD3 (8.0) gave significantly better results than TD2 and TD4. N° leaves/plant for AUG variety (10.23) was significantly higher than NPT variety (8.73). The results indicated that n° leaves/plant, as a parameter, didn't give a clear idea about the effect of different factors on plant growth and development.

Table 5: Total plant and vegetative fresh &amp; dry weight in 2009 &amp; 2010

	Total Plant FW		Vegetative FW		Total Plant DW		Vegetative DW	
	2009	2010	2009	2010	2009	2010	2009	2010
t ha <sup>-1</sup>								
<b>Mulch (M)</b>								
Without	50.8 b	127.4 a	12.68 b	21.1 b	4.2 b	9.5 b	2.5 b	4.2 b
With	86.6 a	145.6 a	15.92 a	30.0 a	6.3 a	12.9 a	3.2 a	6.5 a
<b>Planting (P)</b>								
TD1	65.3	181.7 a	14.2	24.5	5.0	13.4 a	2.7 b	4.9
TD2	72.1	152.2 ab	14.3	25.5	5.5	12.4 a	3.0 ab	5.6
TD3	68.9	127.1 b	15.0	24.5	5.5	10.9 b	3.1 a	5.4
TD4	68.5	86.1 c	13.7	27.0	5.1	8.3 c	2.7 b	5.3
<b>Var (V)</b>								
AUG	62.9 b	122.8 b	13.7 bc	23.5	5.1 b	10.0 b	2.9	5.1
NPT	81.9 a	150.6 a	16.1 a	27.4	5.9 a	12.2 a	3.0	5.6
SAF	64.5 b	-	14.8 ab	-	5.0 b	-	2.8	-
TIZ	65.6 b	-	12.6 c	-	5.1 b	-	2.8	-
<b>Interaction</b>								
MxP	ns	ns	*	ns	ns	ns	ns	ns
MxV	ns	*	ns	ns	ns	*	ns	*
PxV	ns	ns	ns	ns	ns	ns	ns	ns
MxPxV	*	ns	ns	ns	ns	ns	ns	ns

### 2.3.8. Canopy height

In 2009, table 6 is showing that mulching the soil improved significantly the canopy height (0.62 m) more than without using it (0.54 m). Comparing different transplanting dates effect showed significant differences among TD3 (0.65 m), TD2 (0.58 m) and TD1 (0.48 m), while TD4 (0.61 m) didn't give significant differences between it and both TD2 and TD3. Late transplanting improved plant height due to increasing weather temperature at that period compared with the early transplanting dates. Comparing varieties under study,



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NPT variety had higher canopy height (0.62 m) than AUG, SAF, and TIZ varieties which had 0.53, 0.59 and 0.59 m of canopy height, respectively.

In 2010, non-mulched soil gave significantly higher plant canopy (0.41 m) than the height under mulched conditions (table 6). That may be due to the aeration of soil in that rainy season was much better without using mulch, which enhanced root expansion and plant height. The difference of plants canopy height under different TD conditions was not clearly demonstrated showing TD1 and TD3 significantly better than TD2 and TD4. Comparing the two varieties showed that NPT variety (0.40 m) had significantly vigor growth and higher canopy than AUG variety (0.38 m).

### **2.3.9. Maximum leaf area index**

In 2009, under mulched conditions, LAI of tomato plants (1.39) was significantly better than under bare soil conditions (1.12) (table 6). Comparing different transplanting dates, LAI for TD2 (1.29) and TD3 (1.51) were significantly higher compared with TD4 (1.06), while TD1 (1.16) wasn't vary significantly from TD2 and TD4. It didn't be observed a significant difference between LAI of the four varieties under study. This performance could be justified by the effect of mulching on plant growth and resistance under weather conditions of different transplanting dates. The interaction between mulching and both transplanting date and variety affected significantly LAI and consequently plant growth and development.

In 2010, plants gave better LAI (1.96) under mulched conditions, comparing to LAI of plants (1.69) under non-mulched conditions (table 6). Comparing plants under different TDs showed that TD1 (2.67) and TD2 (2.49) gave significantly better LAI than TD3 (1.44), and all the three were significantly than plants of TD4 (0.79). That result favors the early transplanting as it enhances leaf growth and expansion, and subsequently, improves plant photosynthesis. There was a difference between LAI of the two varieties used in this season, giving 2.01 for NPT variety and 1.65 for AUG variety, but it wasn't significant.

### **2.3.10. Harvest index**

In 2009, mulching the soil enhanced harvest index of processing tomato plants (0.48) significantly comparing with plants from non-mulched soil (0.42) (table 6). The difference between effects of transplanting dates showed that TD4 (0.49) and TD2 (0.46)

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gave significantly better HI, with no significant difference between TD3 (0.42) and TD2, and between TD3 and TD1 (0.41). Comparing the four processing tomato varieties didn't show any significant differences among them.

In 2010, table 6 is showing the comparison between plants under mulched and non-mulched conditions showed that mulching soil under that rainy season gave significantly better HI for plants under non-mulched conditions (0.52) than HI for plants under mulched conditions (0.45). Comparing HI of plants under different transplanting dates and of the two varieties didn't show significant differences among them.

### **2.3.11. Classified fruits weight (red, green and rotted fruits)**

#### **2.3.11.1. Red fruits fresh and dry weight**

Fruits were harvested at different dates depending on their maturity at different transplanting dates. It was also done depending on the percentage of red fruits with green and rotted fruits on the plant. Red fruits referred to completely matured fruit and ready to be processed after harvesting. In 2009, table 7 is showing that using mulch improved significantly the red fruits weight (40.39 t ha<sup>-1</sup> fresh and 1.76 t ha<sup>-1</sup> dry) than non-mulched plots (11.92 t ha<sup>-1</sup> fresh and 0.52 t ha<sup>-1</sup> dry). Comparing red tomato weight under different transplanting dates didn't show significant differences among them. Comparing different varieties, NPT showed significantly higher red fruits weight at harvest comparing with the other three varieties. This was due to vigor growth of NPT (35.35 t ha<sup>-1</sup> fresh and 1.54 t ha<sup>-1</sup> dry) variety than the other three varieties under the same conditions.

In 2010, mulching soil didn't affect red fruits fresh and dry weights (table 7). Comparing different transplanting dates showed that TD1 gave significantly better effect on red fruits for both fresh and dry weights (117.73 t ha<sup>-1</sup> fresh and 6.42 t ha<sup>-1</sup>) than the other three TDs, whereas TD2 (84.09 t ha<sup>-1</sup> fresh and 4.51 t ha<sup>-1</sup> dry) and TD3 (73.74 t ha<sup>-1</sup> fresh and 3.65 t ha<sup>-1</sup> dry) were significantly better than TD4 (41.99 t ha<sup>-1</sup> fresh and 2.15 t ha<sup>-1</sup> dry). Comparing the two varieties cultivated in that season, NPT variety gave better results of red fruits for both fresh and dry weights (89.31 t ha<sup>-1</sup> fresh and 4.88 t ha<sup>-1</sup> dry) than AUG variety (69.90 t ha<sup>-1</sup> fresh and 3.51 t ha<sup>-1</sup> dry).

Table 6: Vegetative parameters observed in 2009 and 2010

	n. leaves/ plant		Canopy height (m)		LAI		HI	
	2009	2010	2009	2010	2009	2010	2009	2010
<b>Mulch (M)</b>								
without	17.54	9.04 b	0.54 b	0.41 a	1.12 b	1.69 b	0.42 b	0.52 a
with	18.24	10.02 a	0.62 a	0.37 b	1.39 a	1.96 a	0.48 a	0.45 b
<b>Planting (P)</b>								
TD1	18.21	9.38 ab	0.48 c	0.45 a	1.16 bc	2.67 a	0.41 c	0.53
TD2	18.73	10.95 a	0.58 b	0.37 bc	1.29 ab	2.49 a	0.46 ab	0.41
TD3	18.00	8.00 b	0.65 a	0.42 ab	1.51 a	1.44 b	0.42 bc	0.50
TD4	16.62	9.96 a	0.61ab	0.31 c	1.06 c	0.79 c	0.49 a	0.50
<b>Var (V)</b>								
AUG	17.79 b	10.23 a	0.53 b	0.38 b	1.20	1.65	0.46	0.47
NPT	17.35 b	8.73 b	0.62 a	0.40 a	1.25	2.01	0.47	0.51
SAF	20.33 a	-	0.59 b	-	1.39	-	0.45	-
TIZ	16.09 b	-	0.59 b	-	1.19	-	0.42	-
<b>Interaction</b>								
MxP	ns	ns	ns	**	*	*	ns	ns
MxV	ns	ns	ns	ns	*	ns	ns	ns
PxV	ns	ns	ns	ns	ns	ns	ns	ns
MxPxV	ns	ns	ns	ns	ns	ns	ns	ns

### 2.3.11.2. Green fruits fresh and dry weight

For green fruits weight in 2009, the plants didn't give significant difference under mulching and non-mulching conditions (table 7). Comparing transplanting dates, we found significantly higher green fruits weight under TD1 conditions (9.45 t ha<sup>-1</sup> fresh and 0.50 t ha<sup>-1</sup> dry), followed by TD2 (5.76 t ha<sup>-1</sup> fresh and 0.30 t ha<sup>-1</sup> dry), then TD3 (2.23 t ha<sup>-1</sup> fresh and 0.12 t ha<sup>-1</sup> dry) and TD4 (2.71 t ha<sup>-1</sup> fresh and 0.14 t ha<sup>-1</sup> dry) with no significant difference between the last two. This indicates that choosing transplanting dates and the optimum time to harvest is very critical for both quantity and quality of processing tomato

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fruits. There were no significant differences observed among green fruits weight of different varieties under study.

In 2010, table 7 is showing that mulching the soil gave significantly positive effect on the amount of green fruits (22.58 t ha<sup>-1</sup> fresh and 1.26 t ha<sup>-1</sup> dry) than the amount under non-mulched conditions (13.95 t ha<sup>-1</sup> fresh and 0.72 t ha<sup>-1</sup> dry). Plants under TD1 (29.83 t ha<sup>-1</sup> fresh and 1.65 t ha<sup>-1</sup> dry) and TD2 (28.82 t ha<sup>-1</sup> fresh and 1.55 t ha<sup>-1</sup> dry) conditions gave significantly better green fruits amount than TD3 (11.45 t ha<sup>-1</sup> fresh and 0.59 t ha<sup>-1</sup> dry) and TD4 (4.01 t ha<sup>-1</sup> fresh and 0.22 t ha<sup>-1</sup> dry). NPT variety for green fruits in both fresh and dry weight gave significantly better results (22.45 t ha<sup>-1</sup> fresh and 1.21 t ha<sup>-1</sup> dry) than AUG variety (14.07 t ha<sup>-1</sup> fresh and 0.76 t ha<sup>-1</sup> dry).

### **2.3.11.3. Rotted fruits fresh and dry weight**

The amount of rotted fruits is affected mainly by weather conditions near to harvest time, weed effects around the plants, plant nutritional status, diseases activity at time of maturity. In 2009, table 7 is showing that under mulched conditions the amount of rotted fruits was higher (24.85 t ha<sup>-1</sup> fresh and 1.07 t ha<sup>-1</sup> dry) compared with non-mulched plots (21.61 t ha<sup>-1</sup> fresh and 0.92 t ha<sup>-1</sup> dry). Rotted fruits at late transplanting dates, which are TD2 (26.26 t ha<sup>-1</sup> fresh and 1.11 t ha<sup>-1</sup> dry), TD3 (26.55 t ha<sup>-1</sup> fresh and 1.14 t ha<sup>-1</sup> dry) and TD4 (27.85 t ha<sup>-1</sup> fresh and 1.20 t ha<sup>-1</sup> dry) was significantly higher than TD1 (12.25 t ha<sup>-1</sup> fresh and 0.53 t ha<sup>-1</sup> dry). These results proved that as early is the transplanting dates, as better is the yield quality with less diseases and weather damages. There were no significant differences among varieties for the amount of rotted fruits.

In 2010, the rotted fruits fresh weight was higher under bare soil (15.34 t ha<sup>-1</sup>) more than under non-mulched conditions, while the difference between them for the rotted fruits dry weight wasn't significant (table 7). Comparing the effect of different transplanting dates showed no significant differences for the rotted fruits fresh weight, whereas it was significantly higher amount for the dry matter at TD2 (0.69 t ha<sup>-1</sup>) and TD3 (0.81 t ha<sup>-1</sup>) than TD1 (0.40 t ha<sup>-1</sup>). There were no significant differences between the two tomato varieties in terms of rotted fruits dry weight, while the fresh weight was significantly higher for AUG variety (15.40 t ha<sup>-1</sup>) compared with NPT variety (11.43 t ha<sup>-1</sup>). These results

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confirmed also that as early is the transplanting dates, as better is the yield quality with less diseases and weather damages.

### **2.3.12. Classified fruits number (red, green and rotted fruits)**

From the result of total fruits weight and number of fruits per m<sup>2</sup>, we found that the average weight per fruit in 2009 was around 60 g, while in 2010 it was around 50 g. This finding justified the high number of fruits in 2010 compared with 2009. In addition to that, weather conditions of temperature and precipitation was more favourable for tomato plants in 2010 which was in average 50 mm more in rain and around 3 degrees centigrade more in temperature. Rain frequency was also more in 2010 with about 10 days.

In 2009, mulching the soil gave 125 fruits m<sup>-2</sup> which was significantly higher than the number under non-mulched conditions (76 fruits m<sup>-2</sup>). Comparing different transplanting dates didn't show significant differences among their effects on fruits number. Comparing different varieties showed that NPT (127 fruits m<sup>-2</sup>) had significantly higher fruits number than AUG (93 fruits m<sup>-2</sup>) and SAF (99 fruits m<sup>-2</sup>), whereas AUG didn't vary significantly from TIZ (83 fruits m<sup>-2</sup>).

In 2010, table 8 is showing that plants under mulched conditions gave significantly higher fruits number (300 fruits m<sup>-2</sup>) than plants under non-mulched conditions (227 fruits m<sup>-2</sup>). Plants under TD1 (339 fruits m<sup>-2</sup>), TD2 (279 fruits m<sup>-2</sup>) and TD3 (270 fruits m<sup>-2</sup>) gave significantly higher fruits number than TD4 (162 fruits m<sup>-2</sup>). Comparing the two tomato varieties showed that NPT (312 fruits m<sup>-2</sup>) gave significantly higher fruits number than AUG (216 fruits m<sup>-2</sup>).

#### **2.3.12.1. Red fruits number**

In 2009, table 8 showed that under mulched conditions plants gave red fruits number was significantly higher (64 fruits m<sup>-2</sup>) compared to plants under non-mulched conditions. There was no significant effect of changing TD on red fruits number. NPT gave higher red fruits number compared with the other three varieties.

In 2010, there were no significant differences between plants under mulched and non-mulched conditions (table 8). As early was the transplanting date as higher was the red fruits number per plant giving 219 fruits m<sup>-2</sup> for TD1, 158 fruits m<sup>-2</sup> for TD2, 149 fruits m<sup>-2</sup>

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for TD3, and 94 fruits m<sup>-2</sup> for TD4 which was significantly the lowest number. Comparing the red fruits number of the two varieties showed that NPT gave 181 fruits m<sup>-2</sup> which was significantly higher than AUG red fruits number.

#### **2.3.12.2. Green fruits number**

Green fruits number in 2009 was not differ under mulched and non-mulched soil conditions. TD1 conditions improved significantly green fruits number (26 fruits m<sup>-2</sup>) than the other three transplanting dates. Comparing the behaviour of different varieties didn't show significant differences among them in terms of green fruits number per m<sup>2</sup>.

In 2010, table 8 is showing that mulching the soil improved green fruits number (82 fruits m<sup>-2</sup>) significantly than green fruits number of plants under non-mulched conditions (44 fruits m<sup>-2</sup>). Comparing transplanting dates effect on green fruits number demonstrated that TD1 (94 fruits m<sup>-2</sup>) and TD2 (81 fruits m<sup>-2</sup>) gave significantly higher green fruits number than TD3 (47 fruits m<sup>-2</sup>) and TD4 (31 fruits m<sup>-2</sup>). Comparing the two varieties showed that NPT gave significantly higher green fruits number (81 fruits m<sup>-2</sup>) than AUG (45 fruits m<sup>-2</sup>).

#### **2.3.12.3. Rotted fruits number**

Mulching the soil in both years didn't give significant differences in rotted fruits number than plants under non-mulched conditions (table 8). In 2009, TD1 conditions gave significantly lower rotted fruits number than the late transplanting dates, which were 23 fruits m<sup>-2</sup> for TD1, 51 fruits m<sup>-2</sup> for TD2, 52 fruits m<sup>-2</sup> for TD3, and 51 fruits m<sup>-2</sup> for TD4. NPT (49 fruits m<sup>-2</sup>) and SAF (47 fruits m<sup>-2</sup>) varieties gave significantly higher rotted fruits number than TIZ (38 fruits m<sup>-2</sup>). TIZ was the lowest in the number of rotted fruits compared with the other three varieties.

In 2010, table 8 is showing that TD3 gave the lowest number of rotted fruits (47 fruits m<sup>-2</sup>) compared with the other three transplanting dates. There was no significant differences between the two varieties in terms of rotted fruits number.

Table 7: Comparison of fruit fresh weight at harvest, divided into red, green and rotted fruits, processing tomato varieties and at different transplanting dates in 2009 and 2010

	2009						2010					
	Red		Green		Rotted		Red		Green		Rotted	
	FW	DW	FW	DW	FW	DW	FW	DW	FW	DW	FW	DW
	t ha <sup>-1</sup>						t ha <sup>-1</sup>					
Mulch (M)												
Without	11.92 b	0.52 b	4.62	0.24	21.61 b	0.92 b	77.04	3.88	13.95 b	0.72 b	15.34 a	0.66
With	40.39 a	1.76 a	5.46	0.29	24.85 a	1.07 a	81.52	4.48	22.58 a	1.26 a	11.49 b	0.60
Planting (P)												
TD1	29.41	1.28	9.45 a	0.50 a	12.25 b	0.53 b	117.73 a	6.42 a	29.83 a	1.65 a	9.71	0.40 b
TD2	25.82	1.12	5.76 b	0.30 b	26.26 a	1.11 a	84.09 b	4.51 b	28.82 a	1.55 a	13.81	0.69 a
TD3	25.15	1.09	2.23 c	0.12 c	26.55 a	1.14 a	73.74 b	3.65 b	11.45 b	0.59 b	17.41	0.81 a
TD4	24.24	1.05	2.71 c	0.14 c	27.85 a	1.20 a	41.99 c	2.15 c	4.01 b	0.22 b	13.12	0.62 ab
Var (V)												
AUG	22.36 b	0.97 a	4.72	0.25	22.10	0.95	69.90 b	3.51 b	14.07 b	0.76 b	15.40 a	0.66
NPT	35.35 a	1.54 a	5.47	0.29	25.05	1.08	89.31 a	4.88 a	22.45 a	1.21 a	11.43 b	0.59
SAF	21.83 b	0.95 b	5.08	0.27	22.72	0.96	-	-	-	-	-	-
TIZ	25.08 b	1.09 b	4.87	0.26	23.05	0.99	-	-	-	-	-	-
Interaction												
MxP	ns	ns	**	**	*	*	ns	ns	ns	ns	*	ns
MxV	ns	ns	ns	ns	**	**	ns	ns	ns	ns	ns	ns
PxV	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MxPxV	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 8: Comparison of fruits number at harvest, divided into red, green and rotted fruits, for processing tomato varieties and at different transplanting dates in 2009 and 2010

	n Red fruit		n Green fruit		n rotted fruit		n total fruit	
	2009	2010	2009	2010	2009	2010	2009	2010
$n\ m^{-2}$								
<b>Mulch (M)</b>								
without	20.5 b	143.8	13.7	44.4 b	42.3	39.0	76.1 b	227.1 b
with	64.0 a	166.9	14.8	81.7 a	46.2	51.5	125.1 a	300.1 a
<b>Planting (P)</b>								
TD1	45.8	219.0 a	25.7 a	93.5 a	23.3 b	26.4 b	94.8	338.9 a
TD2	41.8	157.7 ab	14.9 b	80.8 a	50.6 a	40.5 b	106.3	279.0 ab
TD3	42.3	149.4 b	7.5 c	47.1 b	52.4 a	74.0 a	102.2	270.5 b
TD4	39.2	93.7 c	9.0 bc	30.7 b	50.9 a	38.2 b	99.0	162.6 c
<b>Var (V)</b>								
AUG	36.0 b	130.6 b	13.3	45.1 b	43.7 ab	40.4	93.0 bc	216.1 b
NPT	59.9 a	181.3 a	18.2	81.0 a	49.3 a	49.9	127.4 a	312.2 a
SAF	38.2 b	-	14.8	-	46.5 a	-	98.5 b	-
TIZ	35.1 b	-	10.7	-	37.6 b	-	83.4 c	-
<b>Interaction</b>								
MxP	**	ns	**	ns	**	ns	**	ns
MxV	ns	ns	ns	ns	**	*	ns	ns
PxV	ns	ns	ns	ns	*	ns	ns	ns
MxPxV	*	ns	ns	ns	ns	ns	*	ns



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## 2.4. Conclusion

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Under moderate rainy season, mulching the soil is a useful tool to decrease plant water consumption levels and increasing yield and water use efficiency at the transplanting dates studied. The effect of mulching the soil was great due to decreasing soil water evaporation, increasing soil water retention, and increasing the rate of root growth through increasing soil temperature at the root zone. Mulching the soil is also a useful tool to control weeds and to reduce weeds competition with tomato plants on water and nutrients. Since weeds growth needed less water and nutrients than vegetable crops to grow faster and bigger than them, it's essential under dry and relatively hot reasons to manage the weeds in such a way that eliminate weeds growth and to reduce their light, water, and nutrients competition.

Evaluating NPT 63 variety under both soil management conditions, recommended this variety for processing tomato growers due to its vigour characteristics. Plants of this variety gave higher dry biomass accumulation as well as yield compared with the other three varieties studied. This recommends it as a resistant variety against weeds and diseases competition. In addition to growth advantages, it gave also better qualitative yield (more red fruits than rotted fruits), which favour it also in terms of storage, processing, and conservation, and qualitative concerns in the final product.

There was also clear that choosing the optimum harvesting time can increase quantitative and qualitative aspects of the tomato yield. Harvesting at the best time for each transplanting date reduces the percentage of rotted fruits and keeps the storage capacity of the fruits at high levels, removing the risk of mechanic or biological damages of the fruits. This also gives more economic security on selling and distributing the product with relatively higher prices. These considerations increase processing tomato production sustainability, as well as other vegetable crops.

Under rainy season (as the case in 2010), mulching the soil is an added cost without ameliorating yield comparing to non-mulched conditions. This finding is due to the

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homogeneity of water distribution throughout the soil area which balanced the water uptake between the two soil managements, in addition to relatively low temperature during the rainy season at summer time which correspondingly decreased the soil water evaporation even under non-mulched conditions. Early-spring transplanting is the best time for processing tomato in such region (confirmed finding).

The early-spring transplanting in the area under study gave the plants enough time of moderate weather temperature after transplanting to recover from transplanting shock which led at the end of the growing cycle to healthy and strong plants and ended with high yield. The plants at late-spring transplanting were more influenced by any unfavourable weather conditions, i.e. over humid soils which affects root recovering after transplanting or high temperature which cause a sudden drought after some rainy days. All these factors affected negatively the root development and as a result the entire plant nutrient uptake and growth.

NPT 63 variety is a recommended variety under both mulched and non-mulched conditions. This variety, considering almost all the varieties measured, showed fast and strong growth compared with the other three processing tomato varieties studied (confirmed finding). This characteristics gave to this variety many advantages such as weed competitors, disease resistant due to its fast growth avoiding the peaks of pests distribution during the growing cycle. These advantages, especially near to the end of the growing season, are ultimately needed when the temperature and humidity are high giving favourable conditions for both weeds and diseases to grow and distribute in a faster and competitive way.

It is a fundamental qualitative consideration that tomato producers and distributors have to be careful in choosing the harvesting date of the growing vegetable crops. The decision is mainly depends on the weather conditions during the growing cycle. By increasing or decreasing the air temperature and humidity, the fruits are clearly affected and their qualitative value is consequently affected. Choosing the harvesting date for plants at different transplanting dates should be in the way that avoid fruits over maturity as well as mechanical and biological damages, i.e. wind and diseases.

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**Chapter 3**

**Evaluation of CSM-CROPGRO-Tomato Model Using the  
Open Field Experimental Datasets**

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### 3.1. Introduction

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There are only a few models that have been used for the simulation of tomatoes under greenhouse conditions and under field conditions (Rinaldi *et al.*, 2007), and only a few of them simulate growth, development and yield as a function of both local weather and soil conditions.

DSSAT is a software suite contains a collection of independent programs that operate together, with the Cropping System Model (CSM) at its core. DSSAT encompasses models for more than 25 different crops based on various crop and soil modules (i.e. CERES, CROPGRO, CROPSIM, SUBSTOR, and CENTURY) with software that facilitates the evaluation and application of the crop models for different purposes (Hoogenboom *et al.*, 2003). It is a package of cropping system models that includes special programs to create databases on crop experiments (including crop management treatments as well as measurements made on crop development during the life cycle), on soil parameters and on climatic data.

Such kind of software helps users with the preparation of these databases and to compare simulated results with observations to give them confidence in the models or to determine if modifications are needed to improve accuracy (Uehara, 1989; Jones *et al.*, 1998).

CROPGRO was created after adapting experience of SOYGRO to PNUTGRO and BEANGRO (Hoogenboom *et al.*, 1994) having the idea of one common program with values from files providing information for each species to be modelled. Currently, it simulates ten crops; including seven grain legumes, and non-legumes such as tomato (*Lycopersicon esculentum* Mill.) (Scholberg *et al.*, 1997; Boote *et al.*, 1998a, b).

A number of models have been developed for tomato in order to predict different growth and production parameters (Wolf *et al.*, 1986; Bertin and Gray 1993; Heuvelink and Marcelis 1993; and Jones *et al.*, 1989). Jones *et al.* (1991) have developed TOMGRO growth model for greenhouse tomato, but Scholberg *et al.* (1997) found that TOMGRO did not adequately describe the growth of field-grown tomatoes. Subsequently, Scholberg *et al.* (1997) adapted the CROPGRO-Peanut model establishing CROPGRO-Tomato model in order to simulate growth, yield and yield components of the field-grown tomatoes. Modelling the

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growth of field-grown tomatoes should assist growers and extension workers throughout the world to outline optimal crop management strategies for specific locations and protection systems (Scholberg *et al.*, 1997).

In this study a beta version of DSSAT v4.5 (Hoogenboom *et al.*, 2009) was used to simulate growth, development and yield for tomato using the CSM-CROPGRO-Tomato (Jones *et al.*, 2003). The CSM-CROPGRO-Tomato model allows for the simulation of tomato growth over a wide range production systems (Scholberg *et al.*, 1997).

The main objective of this study was to evaluate growth, yield, and yield components of the CSM-CROPGRO-Tomato model for field grown processing tomato at different transplanting dates and associated weather conditions. The experiments were conducted in northeastern Italy, representing typical conditions for processing tomatoes.

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## **3.2. Materials and Methods**

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### **3.2.1. The model used in study**

To better understand how CSM-CROPGRO-Tomato model deals with tomato growing cycle, according to Hoogenboom *et al.* (1991) it can be divided into seven main stages, which are:

1. Emergence (V-0),
2. First full leaf (unifoliate) V-1,
3. End of juvenile phase,
4. Flowering induced (R0),
5. First flower appearance (R1),
6. First pod appearance (R3 = NPOD 0),
7. First full pod (R4 = NR3),
8. First full-sized seed appearance (R5),
9. End of pod addition stops (NDSET),
10. Physiological maturity (R7),
11. Harvest maturity (R8),
12. End of main stem (vegetative) growth,
13. End of leaf expansion (NDLEAF).

### **3.2.2. Processing tomato varieties used in calibration and validation phases**

Two open-field experiments were conducted in 2009 and 2010, and described in chapter 2, in order to obtain observed datasets ready to be used in calibration and validation phases of the CSM-CROPGRO-Tomato model, respectively. In 2009, calibrating the model was done through the four processing tomato varieties were cultivated in the experiment,



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which were Augusto F1 (AUG) and Tiziano F1 (TIZ) from De Ruiter company; and NPT 63 (NPT) and Safaix (SAF) from S&G company. Validating the model was done through Augusto F1 (AUG) and NPT 63 (NPT) varieties which were cultivated in 2010 as two examples of a vigor variety (NPT) and a moderate growth variety (AUG). Detailed information about seedlings of each variety at transplanting time were used as initial characteristics, they are explained in table 5.

Seedlings were transplanted in the open field with 10 days interval between the four transplanting dates (TD1, 2, 3, and 4). The open field experiment was started on 21st April and was finished on 2nd September in 2009, whereas it was started on 29th April and was finished on 30th August in 2010. Details about irrigation system and fertilization for both experiments are described in chapters 1 and 2.

### **3.2.3. Datasets used to evaluate the model**

In this study, the CSM-CROPGRO-Tomato model was evaluated using the non-mulched experimental datasets, which was the environmental condition that was used for initial model development. Experimental data were adjusted and some of them were calculated in order to fit model format. Compiled data sets collected biweekly were entered into the time course data file (FileT) and the final compiled data set was entered into the summary data file (FileA). The experimental management details were entered into experimental detail file (FileX) using DSSAT V4.5 standardised format of XBuild program (Hoogenboom *et al.*, 2009). Soil profile descriptions for the experimental location were added to SOIL.SOL file of the SBuild program of DSSAT shell. Daily weather data set collected for the location was placed in the weather data files of the Weatherman program of DSSAT shell (FileW).

Table 9: Characteristics and nursery conditions of tomato seedlings at transplanting

Characteristics	TD	AUG		NPT		SAF	TIZ
		2009	2010	2009	2010	2009	2009
<b>Seedling dry weight (g/seedling)</b>	1	5.54	5.55	10.6	10.7	4.78	6.04
	2	13.9	28.4	23	23.2	17.1	15.3
	3	18.8	12.5	21.7	17.9	16.7	17.8
	4	18	19	26.9	18.8	23.2	20.2
<b>Age (days from sowing to transplanting)</b>	1	24	38	24	38	24	24
	2	32	46	32	46	32	32
	3	31	38	31	38	31	31
	4	31	38	31	38	31	31
<b>Average Temperature during nursery period (°C)</b>	1	23.4	18.9	23.4	18.9	23.4	23.4
	2	22.4	19.6	22.4	19.6	22.4	22.4
	3	25.6	21.3	25.6	21.3	25.6	25.6
	4	34.2	22	34.2	22	34.2	34.2
<b>N° plants per hill</b>	1	1	1	1	1	1	1
	2	1	1	1	1	1	1
	3	1	1	1	1	1	1
	4	1	1	1	1	1	1
<b>Sprout length (cm)</b>	1	15	13	15	15	15	15
	2	15	17	15	20	15	15
	3	15	13	15	15	15	15
	4	20	15	20	17	20	20

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#### **3.2.3.1. Time course data file (FileT)**

The plant parameters inserted in this file were: vegetative dry matter accumulation ( $\text{kg ha}^{-1}$ ), total dry matter accumulation ( $\text{kg ha}^{-1}$ ), number of leaves on the main stem ( $\text{n}^\circ \text{ plant}^{-1}$ ), canopy height development ( $\text{cm plant}^{-1}$ ), leaf area index development, fruit fresh weight accumulation ( $\text{kg ha}^{-1}$ ), fruit dry matter accumulation ( $\text{kg ha}^{-1}$ ), number of fruits development ( $\text{n}^\circ \text{ m}^{-2}$ ), and harvest index development.

#### **3.2.3.2. Summary data file (FileA)**

Codes of the observation dates used in the model evaluation were: planting date, anthesis date, first fruit set date, and maturity date. The plant parameters inserted in this file were: total plant dry matter at maturity, fruit fresh weight at maturity, fruit dry matter at maturity, harvest index at maturity, number of fruits at maturity, maximum leaf area index, and number of leaves on the main stem at maturity.

#### **3.2.3.3. Experimental detail file (FileX)**

Details about experiment location and year of the experiment were inserted in this file, in addition to treatments, cultivars, planting and management information. A detailed example for the 2010 experimental datasets file is provided in appendix 1.

#### **3.2.3.4. Soil file (SOIL.SOL)**

Information about soil analysis of the location under study was prepared as a soil profile input in the standard soil profiles file. The profile was divided into 5 levels; each level represents 20 cm of soil depth (Table 10). For each soil level, analysis was made, and according to those analysis, the model was able to calculate and give other characteristics such as drained upper limit, saturation, bulk density ( $\text{g.cm}^3$ ), saturation hydraulic conduct ( $\text{cm/h}$ ), and root growth factor (from 0 to 1). A detailed standard soil profile file is provided in appendix 2.

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#### **3.2.3.5. Weather data file (FileW)**

Weather data for both 2009 and 2010 years were formed in the weather format. The minimum weather parameters for the model were provided which are: solar radiation ( $\text{MJ.m}^2$ ), minimum temperature ( $^{\circ}\text{C}$ ), maximum temperature ( $^{\circ}\text{C}$ ), and precipitation (mm). Monthly averages for both years are provided in Figure 14.

Table 10: Characteristics and profile of the experiment soil located in Agripolis, L. Toniolo (45° 21' N; 11° 58' E), Italy

<b>Soil classification</b>	Loamy						
<b>Color</b>	Brown						
<b>Drainage</b>	Well						
<b>Slope</b>	3						
<b>Runoff potential</b>	Relatively low						
<b>Fertility factor</b>	1						
<b>Soil Profile</b>	<b>0</b>	<b>20</b>	<b>40</b>	<b>80</b>	<b>100</b>	<b>120</b>	<b>180</b>
Clay (%)	15.4–18.6	15.4–18.6	15.5–18.6	15.6–17.4	14.8	18.4	28.7
Silt (%)	41.3–46.6	41.3–46.6	41.3–46.5	44.2–47.4	50.0	57.7	52.8
Organic carbon (%)	1.2–1.8	1.1–1.6	1.1–1.4	0.7	0.2	0.7	0.2
pH in water	8.0–8.4	8.0–8.3	8.0–8.3	8.0–8.4	8.0–8.4	8.0	8.0
CEC	14.8	14.8	14.8	14.8	14.8	14.8	14.8

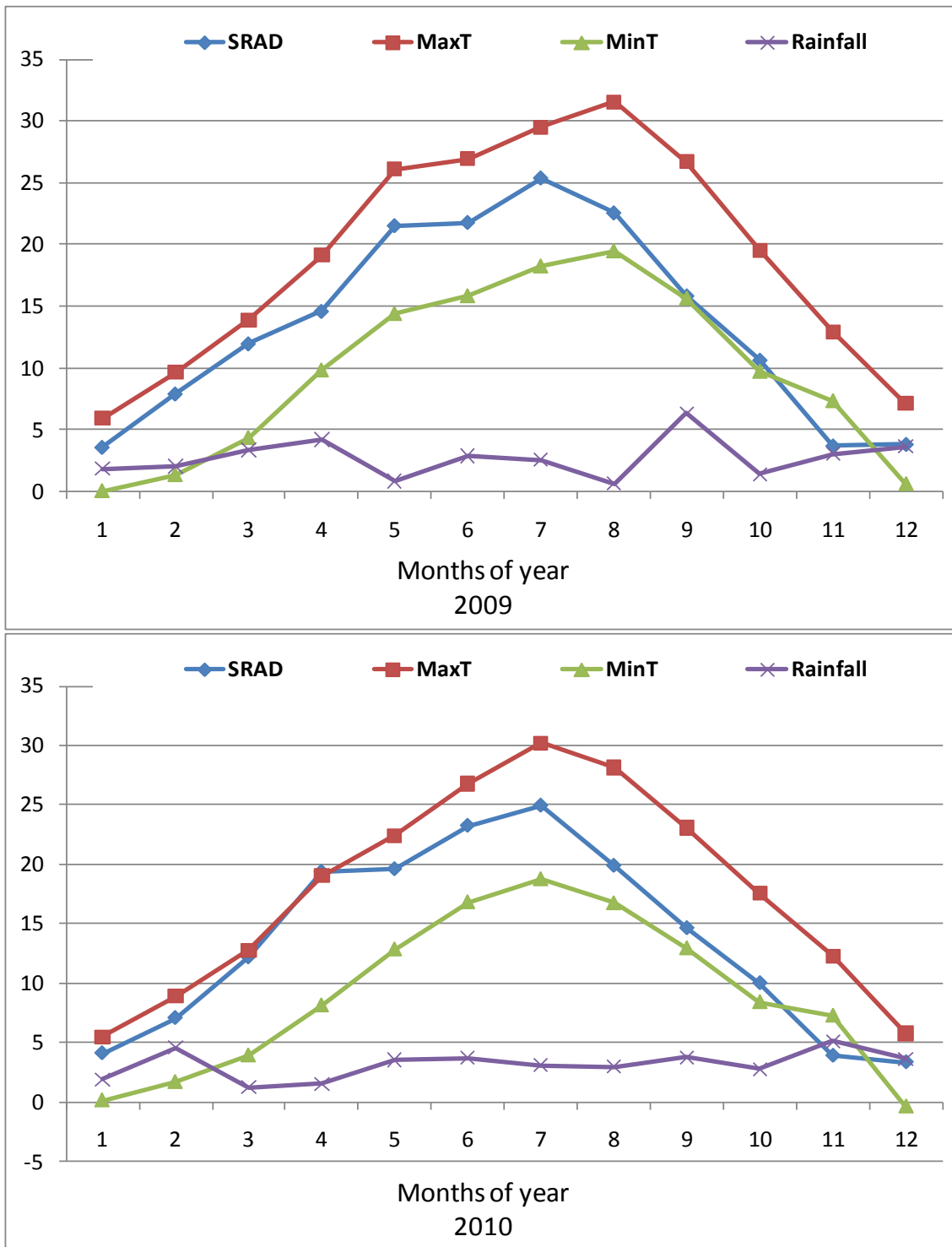


Figure 14: Weather conditions in experimental grown processing tomato seasons of 2009 and 2010.

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### 3.2.4. Model evaluation

There are different statistic indexes that comes with the model output files, including, the normalized root mean square error (RMSE) that is expressed in percent, calculated as explained by Loague and Green (1991) with the help of following Equation:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \times \frac{100}{M}$$

where  $n$  is the number of observations,  $P_i$  and  $O_i$  are predicted and observed values respectively,  $M$  is the observed mean value. RMSE gives a measure (%) of the relative difference of simulated vs. observed data. The simulation is considered excellent with  $\text{RMSE} < 10\%$ , good if 10–20%, fair if 20–30%, poor  $> 30\%$  (Jamieson *et al.*, 1991). For yield and yield components, the mean square error (MSE) was calculated into a systematic (MSEs) and unsystematic (MSEu) component as it is explained by Willmott (1981). The Index of Agreement ( $d$ ) as described by Willmott *et al.* (1985) was estimated as shown in the following equation:

$$d = 1 - \left[ \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P'_i| + |O'_i|)^2} \right]$$

where  $n$  is the number of observations,  $P_i$  the predicted observation,  $O_i$  is a measured observation,  $P'_i = P_i - M$  and  $O'_i = O_i - M$  ( $M$  is the mean of the observed variable). So if the  $d$ -statistic value is closer to one, then there is good agreement between the two variables that are being compared and vice versa, so it is very important that if value varies from value of one then there will be weak agreement of the variable that we are being compared with each other.

Using the sensitivity analysis option of the model, the cultivar coefficients of the two varieties were adjusted by minimizing RMSE values between observed and simulated flowering and maturity dates, vegetative growth, yield and yield components (Table 6). Correlation analysis for harvest index between observed and simulated output values were obtained using the standard error of the “Excel- Microsoft” program.

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Systematic approach and order for calibration (Boote, 1999) were, taking into consideration that these steps are for all CROPGRO crops including tomato:

STEP 1. CROP LIFE CYCLE

The first step should be to simulate crop development (flowering date and maturity date) of the cultivar being calibrated using the actual weather data.

STEP 2. DRY MATTER ACCUMULATION

This step involves simulating rate of dry matter accumulation and comparing simulated to observed values.

STEP 3. LEAF AREA INDEX AND SPECIFIC LEAF AREA (SLA)

Several “cultivar” parameters have a small impact on dry matter accumulation via their effect on LAI and light interception. These include specific leaf area (SLAVR), time to cessation of leaf area expansion (FL-LF), SIZLF (early “sink” limited leaf area expansion), If the data of LAI and SLA, plot these. If predicted SLA is too high, decrease SLAVR. If SLA is too low, increase SLAVR. Now LAI should be closer to the observed (at least if leaf weight was correctly predicted).

STEP 4. RE-CALIBRATE DRY MATTER ACCUMULATION

Use the calibrated SLA and leaf area timing aspects from step 3 and recalibrate dry matter accumulation as in step 2.

STEP 5. “SPECIES” PARAMETER EFFECTS ON PHOTOSYNTHESIS AND DRY MATTER ACCUMULATION

The parameters influencing photosynthetic response to N concentration probably have the largest effect. These species parameters have their signature effects at different times and on different processes.

STEP 6. INITIAL CALIBRATION FOR SEED SIZE, SEEDS PER PODS AND SEED FILLING DURATION

STEP 7. INITIAL TIMING AND INITIAL RISE IN POD AND SEED DRY WEIGHT

Now adjust the timing from flowering to first pod (FL-SH) and the timing from first flower to first seed (FL-SD) and duration of pod addition (PODUR), to get the correct



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timing to the initial rise in pod dry weight and seed dry weight. Take into consideration the main economically harvested part either seed or fruit.

**STEP 8. RE-CALIBRATE TIME FROM FIRST SEED TO MATURITY**

If FL-SD (time to beginning seed) was calibrated, adjust SD-PM (Time between first seed and physiological maturity, time between first seed and physiological maturity, in order to again correctly predict the observed date of physiological maturity.

**STEP 9. RE-EVALUATE TOTAL DRY MATTER ACCUMULATION AND RELATIVE PARTITIONING BETWEEN VEGETATIVE AND REPRODUCTIVE STAGES.**

Are fruit addition, and phenology timing correct? If so, reevaluate dry matter accumulation fruit mass and total aboveground biomass and the relative partitioning between fruit and shoot mass.

For further details about CROPGRO calibration steps followed in this study please refer to the model manuals (Boote, 1999).

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### 3.3. Results and Discussion

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#### 3.3.1. Calibration of CSM-CROPGRO-Tomato model

CSM-CROPGRO-Tomato model was calibrated for field-grown determinate processing tomato using four varieties at four different transplanting dates under bare soil conditions. This calibration was achieved comparing the input data from experimental year 2009 conducted at Agripolis, in northeastern Italy, with the simulated values comes out from the model. Evaluating simulation ability of CSM-CROPGRO-Tomato model was done using the d-Stat index values (Willmott, *et al.* 1985) and RMSE values (Loague and Green, 1991).

Table (11) shows the cultivar coefficients were evaluated during calibration phase. Phenological coefficients that affected model simulation for different cultivar parameters were: the photothermal days of: time between plant emergence and flower appearance (EM-FL); time between first flower and first pod (FL-SH); time between first flower and first seed (FL-SD); time between first seed and physiological maturity (SD-PM); time between first flower and end of leaf expansion (FL-LF); seed filling duration for pod cohort at standard growth conditions (SFDUR); and time required for cultivar to reach final pod load under optimal conditions (PODUR). FL-SD was reduced from 17 (default value) to 14 photothermal days for AUG variety. SD-PM was reduced from 50 (default value) to 38 photothermal days for AUG variety. FL-LF was reduced from 50 (default value) to 42 photothermal days for AUG variety. SFDUR was reduced from 25 (default value) to 20 photothermal days for AUG variety. PODUR didn't change from the default value which is 42 photothermal days for AUG variety.

The vegetative growth coefficients in cultivar file evaluated during calibration phase (table 11) were: maximum leaf photosynthesis rate at 30 °C, 350 vpm CO<sub>2</sub>, and high light (LFMAX); specific leaf area of cultivar under standard growth conditions (SLAVR); maximum size of full leaf (SIZLF); maximum weight per seed (WTPSD); and threshing percentage. The maximum ratio of (seed/(seed+shell)) at maturity causes seed to stop growing as their dry weight increases until the shells are filled in a cohort (THRSH). LFMAX didn't

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change from the default value for AUG variety, whereas SLAVR, which is responsible for leaf expansion on the plant occupied area, was decreased from 350 (default value) to 200 cm<sup>2</sup> g<sup>-1</sup>. SIZLF, which is responsible for full single leaf size, was decreased from 300 (default value) to 170 cm<sup>2</sup>. WTPSD, which is affecting fruits weight and number, was decreased from 0.0040 (default value) to 0.0025 g. THRSR, which is affecting fruit weight, was decreased from 9.2 (default value) to 8.2 %.

Vegetative partitioning parameters in the species file was evaluated gradually and adjusted according to partitioning rate for leaf and stem observations (table 12). Plant growth simulation showed a strong sensitivity to leaf characteristics, hence, estimated parameters of leaf growth from experimental data were used and changes were made in the species file parameters (Rinaldi *et al.*, 2007). Leaf growth parameters evaluated also during calibration phase were: specific leaf area of leaves at plant emergence (FINREF); specific leaf area of the standard reference cultivar at peak early vegetative phase, under optimum temperature, water, and light (SLAREF); maximum specific leaf area (SLAMAX); minimum specific leaf area (SLAMIN); respective maximum leaf area (cm<sup>2</sup> plant<sup>-1</sup>) at corresponding V stage, part of possible limiting leaf area expansion for first nodes (YVREF); and relative temperature effect on specific leaf area of newly-formed leaves (YSLATM). FINREF was reduced from 200 (default value) to 85 cm<sup>2</sup> g<sup>-1</sup>. SLAREF was reduced from 245 (default value) to 136 cm<sup>2</sup> g<sup>-1</sup>. SLAMAX was reduced from 500 (default value) to 400 cm<sup>2</sup> g<sup>-1</sup>. SLAMIN was reduced from 250 (default value) to 80 cm<sup>2</sup> g<sup>-1</sup>. YVREF and YSLATM parameters were changed gradually until simulated values nearly matched observed values.

Table 11: Cultivar coefficients that were modified during calibration phase of the CSM-CROPGRO-Tomato model for the four tomato varieties under study (TOMGRO045.CUL file)

Cultivar Coefficient	Default values	Calibrated values			
		AUG	NPT	SAF	TIZ
1. EM-FL: Time between plant emergence and flower appearance (R1) (photothermal days)	23	23	23	23	23
2. FL-SH: Time between first flower and first pod (R3) (photothermal days)	8	8	8	8	8
3. FL-SD: Time between first flower and first seed (R5) (photothermal days)	17	<u>14</u>	<u>14</u>	<u>14</u>	<u>14</u>
4. SD-PM: Time between first seed (R5) and physiological maturity (R7) (photothermal days)	50	<u>38</u>	<u>38</u>	<u>38</u>	<u>38</u>
5. FL-LF: Time between first flower (R1) and end of leaf expansion (photothermal days)	50	<u>42</u>	<u>42</u>	<u>42</u>	<u>42</u>
6. LFMAX: Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO <sub>2</sub> , and high light (mg CO <sub>2</sub> m <sup>-2</sup> s <sup>-1</sup> )	1.36	1.36	1.36	1.36	1.36
7. SLAVR: Specific leaf area of cultivar under standard growth conditions (cm <sup>2</sup> g <sup>-1</sup> )	350	<u>200</u>	<u>220</u>	<u>220</u>	<u>250</u>
8. SIZLF: Maximum size of full leaf (three leaflets) (cm <sup>2</sup> )	300	<u>170</u>	<u>190</u>	<u>190</u>	<u>200</u>
9. WTPSD: Maximum weight per seed (g)	0.0040	<u>0.0025</u>	<u>0.0030</u>	<u>0.0025</u>	<u>0.0035</u>
10. SFDUR: Seed filling duration for pod cohort at standard growth conditions (photothermal days)	25	<u>20</u>	25	25	25
11. PODUR: Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	42	42	42	42	42
12. THRSH: Threshing percentage. The maximum ratio of (seed/(seed+shell)) at maturity causes seed to stop growing as their dry weight increases until the shells are filled in a cohort.	9.2	9.2	9.2	9.2	9.2

Table 12: Species coefficients that were modified during calibration phase of the CSM-CROPGRO-Tomato model for the four tomato varieties under study (TOMGRO045.SPE file)

Species Coefficient	Default values	Calibrated values
1. Vegetative partitioning parameters	XLeaf: 0.0-6.1-8.3-10.3-12.3-14.6-16.9-18.4-19.5-22.1 YLeaf: 0.40-0.45-0.65-0.70-0.70-0.70-0.70-0.70-0.60-0.60 YStem: 0.30-0.25-0.20-0.20-0.20-0.20-0.20-0.20-0.30-0.30	XLeaf: 0.0-16.1-17.3-20.3-22.3-24.6-26.9-28.4-29.5-29.1 YLeaf: 0.45-0.45-0.58-0.55-0.62-0.58-0.55-0.52-0.51-0.47 YStem: 0.3-0.3-0.37-0.31-0.35-0.39-0.34-0.37-0.39-0.34
2. Leaf growth parameters		
• FINREF: The specific leaf area ( $\text{cm}^2\text{g}^{-1}$ ) of leaves at plant emergence, scaled via SLAVR	200	85
• SLAREF: The specific leaf area ( $\text{cm}^2\text{g}^{-1}$ ) of the standard reference cultivar at peak early vegetative phase, under optimum temperature, water, and light.	245	136
• SLAMAX: Maximum specific leaf area ( $\text{cm}^2\text{g}^{-1}$ )	500	400
• SLAMIN: Minimum specific leaf area ( $\text{cm}^2\text{g}^{-1}$ )	250	80
• YVREF(1-6): Respective maximum leaf area ( $\text{cm}^2\text{plant}^{-1}$ ) at corresponding V stage, part of possible limiting leaf area expansion for first (VSSINK) nodes	15.4-28.1-83.4-210.0-340.0-500.0	15.4-128.1-300.4-500.0-1000.0-2000.0
• YSLATM(1-5): Relative temperature effect on specific leaf area of newly-formed leaves ( $\text{cm}^2\text{g}^{-1}$ )	0.48-0.48-0.48-0.50-0.50	0.50-0.60-0.90-1.00-1.00

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### 3.3.1.1. Total dry matter accumulation

In the four sampling dates was taken during field experiment period, accumulation of the above ground part of tomato plants was measured as parameters to evaluate the performance of CSM-CROPGRO-Tomato model. For all the four varieties used in spring 2009 growing season, we were able to arrive to acceptable matching levels between observed values from the field and model simulation values. The main statistical indices used to evaluate calibration of the model are reported.

Comparing the simulated vs. observed values for total dry matter accumulation of Augusto F1 plants we found that model d-Stat values between simulated and observed values at four different transplanting dates for AUG variety were 0.809, 0.989, 0.961 and 0.990, respectively. RMSE values at different transplanting dates for AUG variety were 771, 244.8, 431, and 312.2 kg ha<sup>-1</sup>, respectively (Figure 15). NPT variety had better simulation giving 0.923, 0.965, 0.926 and 0.990 as d-Stat values; and giving 665.8, 575.6, 789.6 and 315.1 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 16). RMSE values for NPT variety were higher than the other three varieties as it gave higher total plant dry matter. SAF variety had also very good simulation, giving 0.964, 0.987, 0.968 and 0.989 as d-Stat values; and giving 452.8, 279.0, 420.2 and 324.0 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 17). Plants of TIZ variety had an acceptable simulation for TD1 and very good simulation for the other three transplanting dates giving 0.677, 0.954, 0.970 and 0.967 as d-Stat values; and giving 1368.3, 612.9, 515.7 and 577.4 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 18).

At the first transplanting date, the matching between simulated and observed weight was high at the beginning of growing cycle after transplanting, then it was slightly overestimated near to the end of the growing cycle. This could be due to unfavourable weather conditions at transplanting time and the short period after, which is necessary for the plant to hold on and continue till the end of its life cycle. The model was able to simulate total dry matter accumulation at other three transplanting dates.

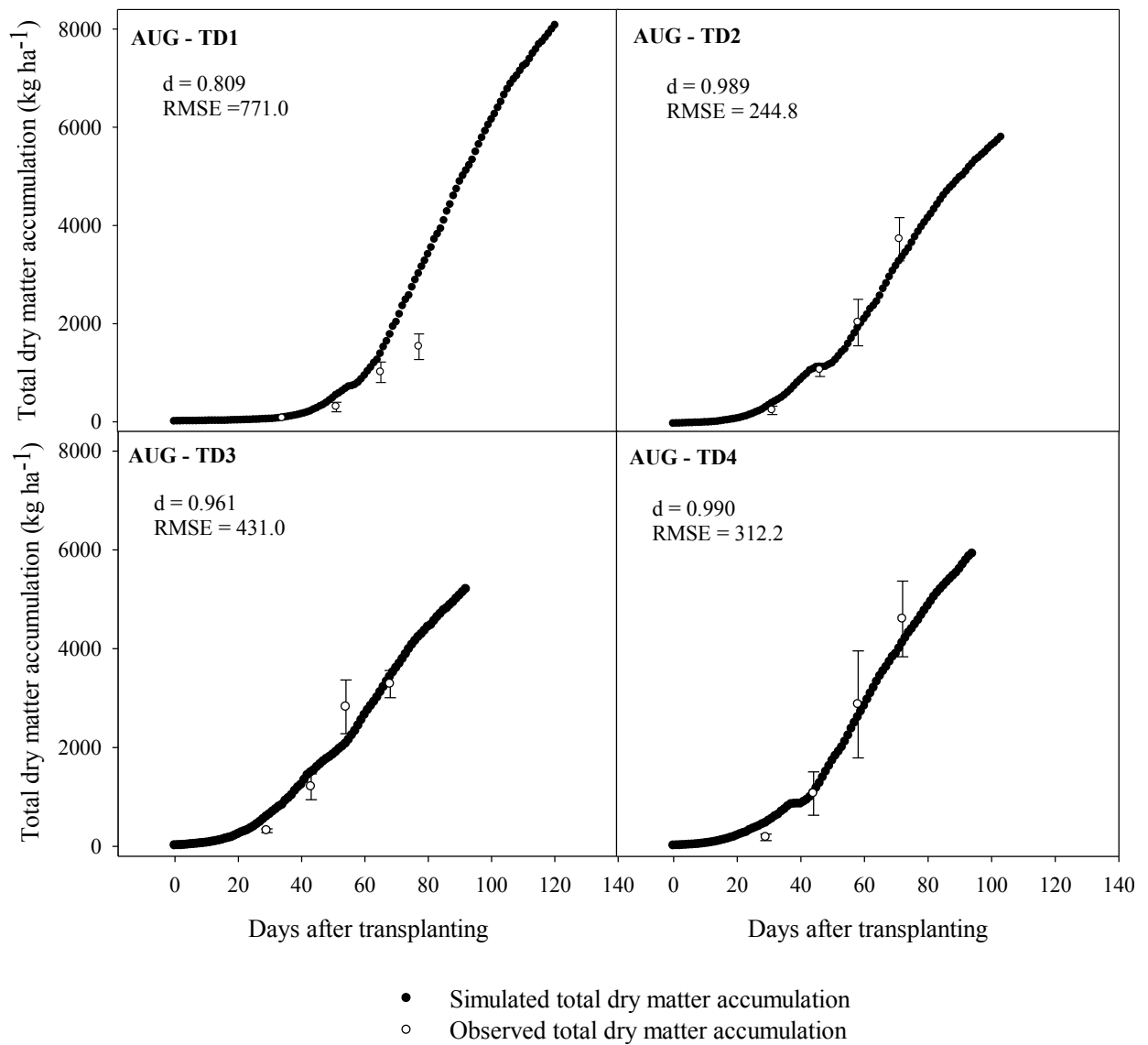


Figure 15: Simulated and observed total dry matter accumulation (TDM) for AUG processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

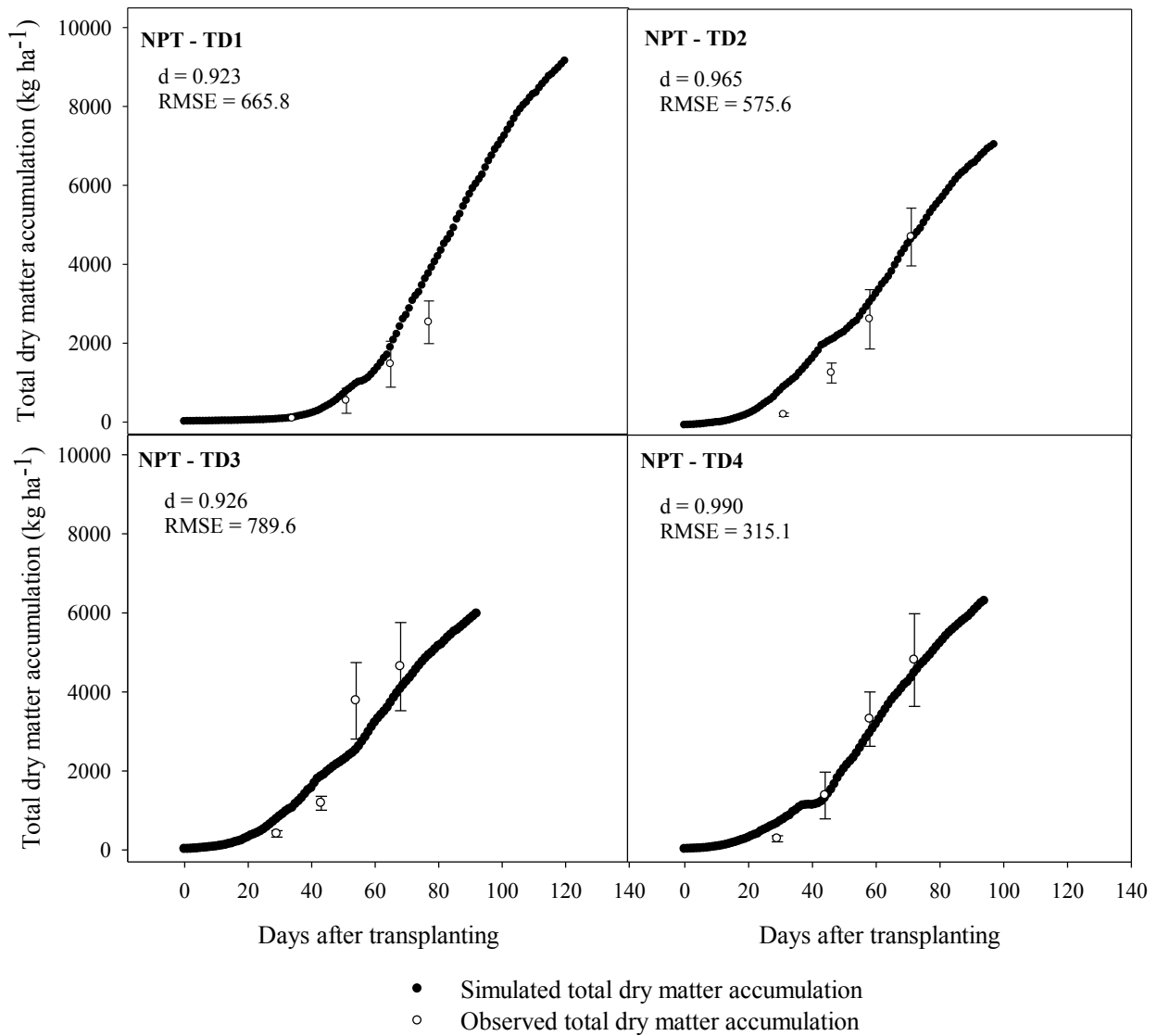


Figure 16: Simulated and observed total dry matter accumulation (TDM) for NPT processing tomato variety at the four different transplanting dates during the spring 2009 growing season.



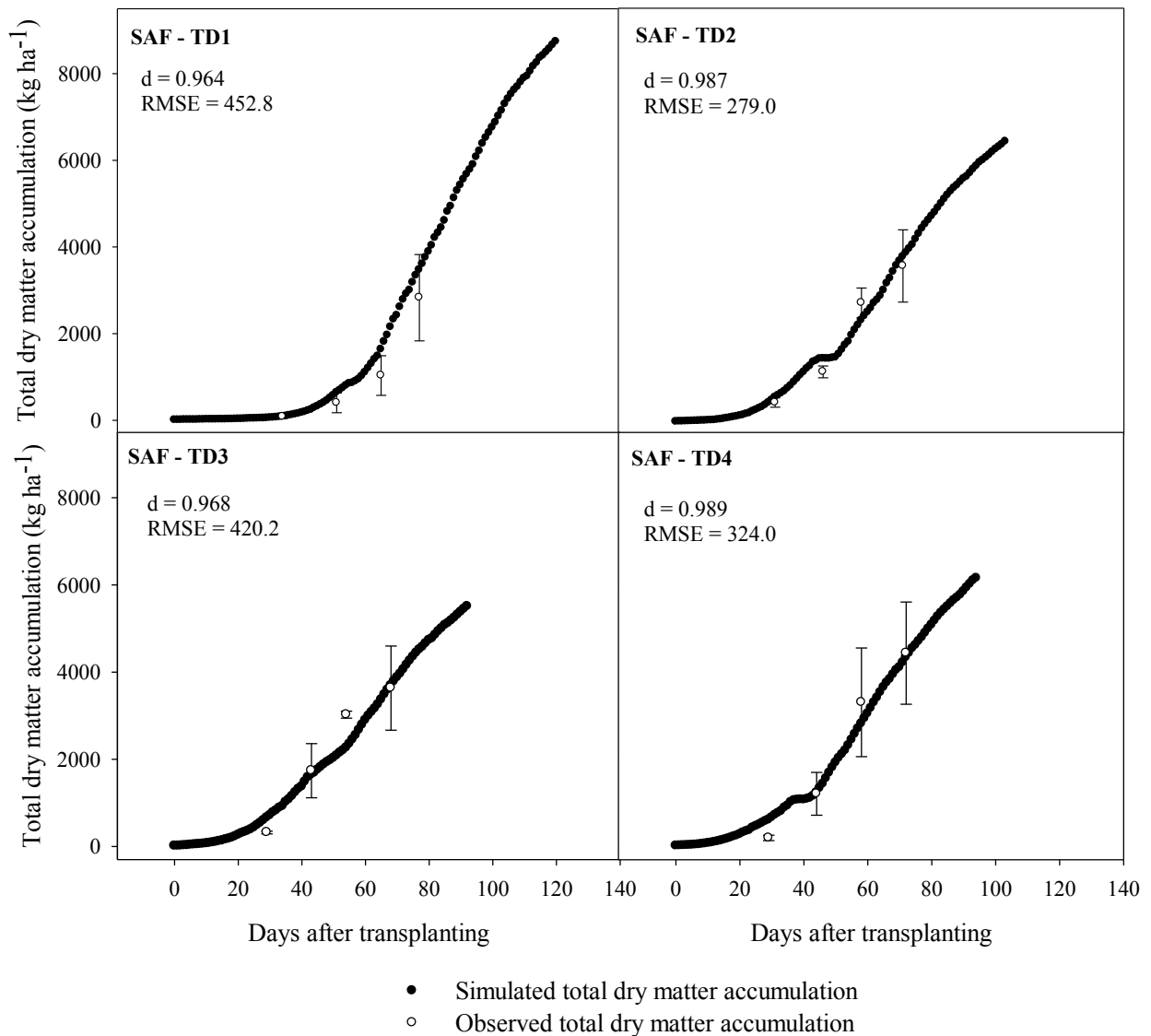


Figure 17: Simulated and observed total dry matter accumulation (TDM) for SAF processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

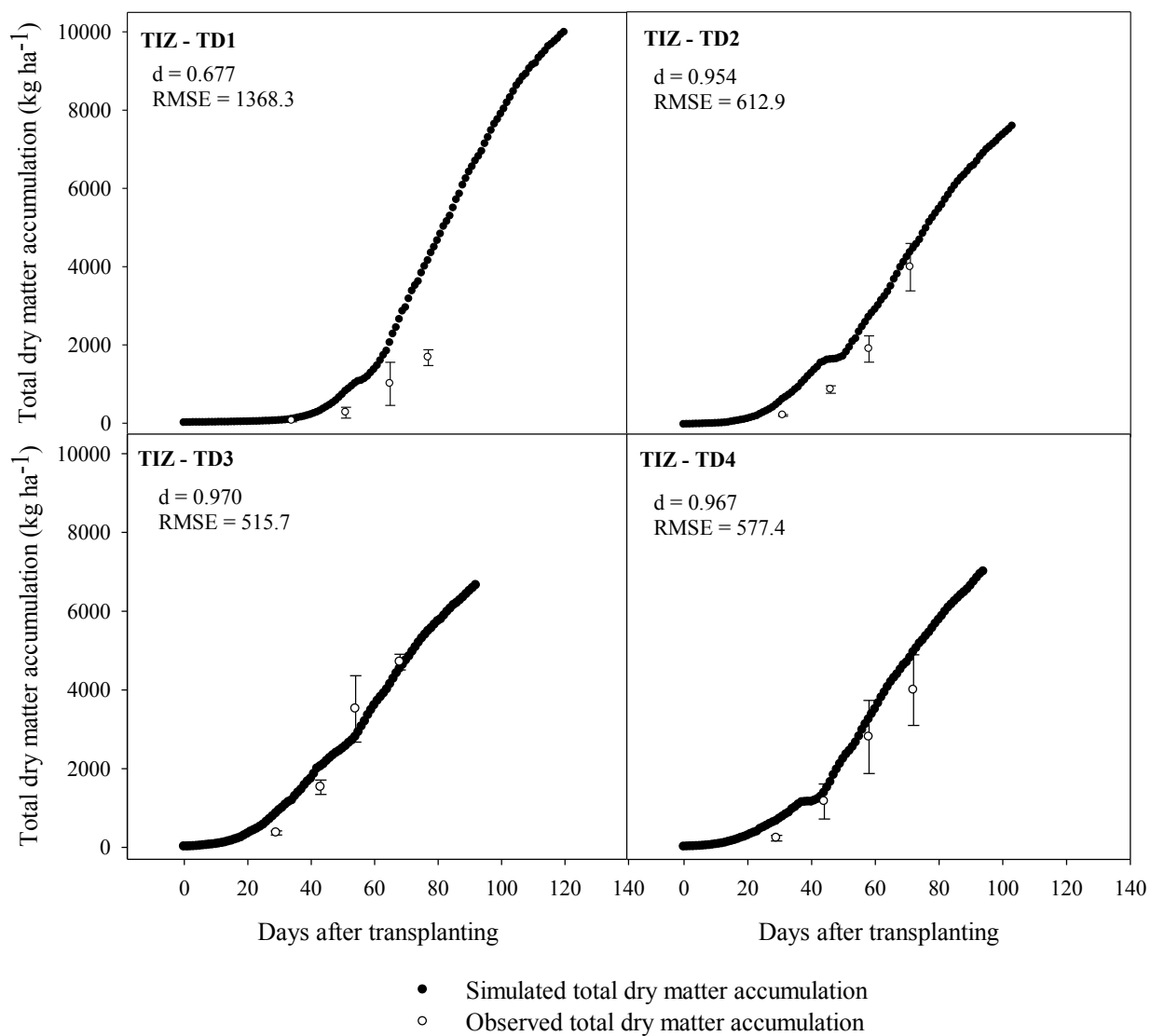


Figure 18: Simulated and observed total dry matter accumulation (TDM) for TIZ processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

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### 3.3.1.2. Fruits dry matter accumulation

Comparing model performance at different transplanting dates for AUG variety showed that d-Stat values between observed and simulated fruits dry matter accumulation were 0.653, 0.972, 0.918, and 0.993, respectively, while RMSE values were 488, 228.2, 334.5, and 156.6 kg ha<sup>-1</sup>, respectively (Figure 19). NPT variety had better simulation giving 0.910, 0.992, 0.962 and 0.995 as d-Stat values; and giving 343.2, 164.6, 302.6 and 137.7 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 20). SAF variety had also very good simulation, giving 0.920, 0.939, 0.978 and 0.949 as d-Stat values; and giving 306.0, 326.6, 206.4 and 388.2 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 21). Plants of TIZ variety had an acceptable simulation for TD1 and very good simulation for the other three transplanting dates giving 0.562, 0.955, 0.923 and 0.831 as d-Stat values; and giving 617.7, 349.0, 452.4 and 784.1 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 22).

These results indicate that the model performance at TD1 was lower than at the other three transplanting dates. The reason for model over prediction in TD1 could be due to the inaccurate response of the model at low weather temperature which occurred at early transplanting.

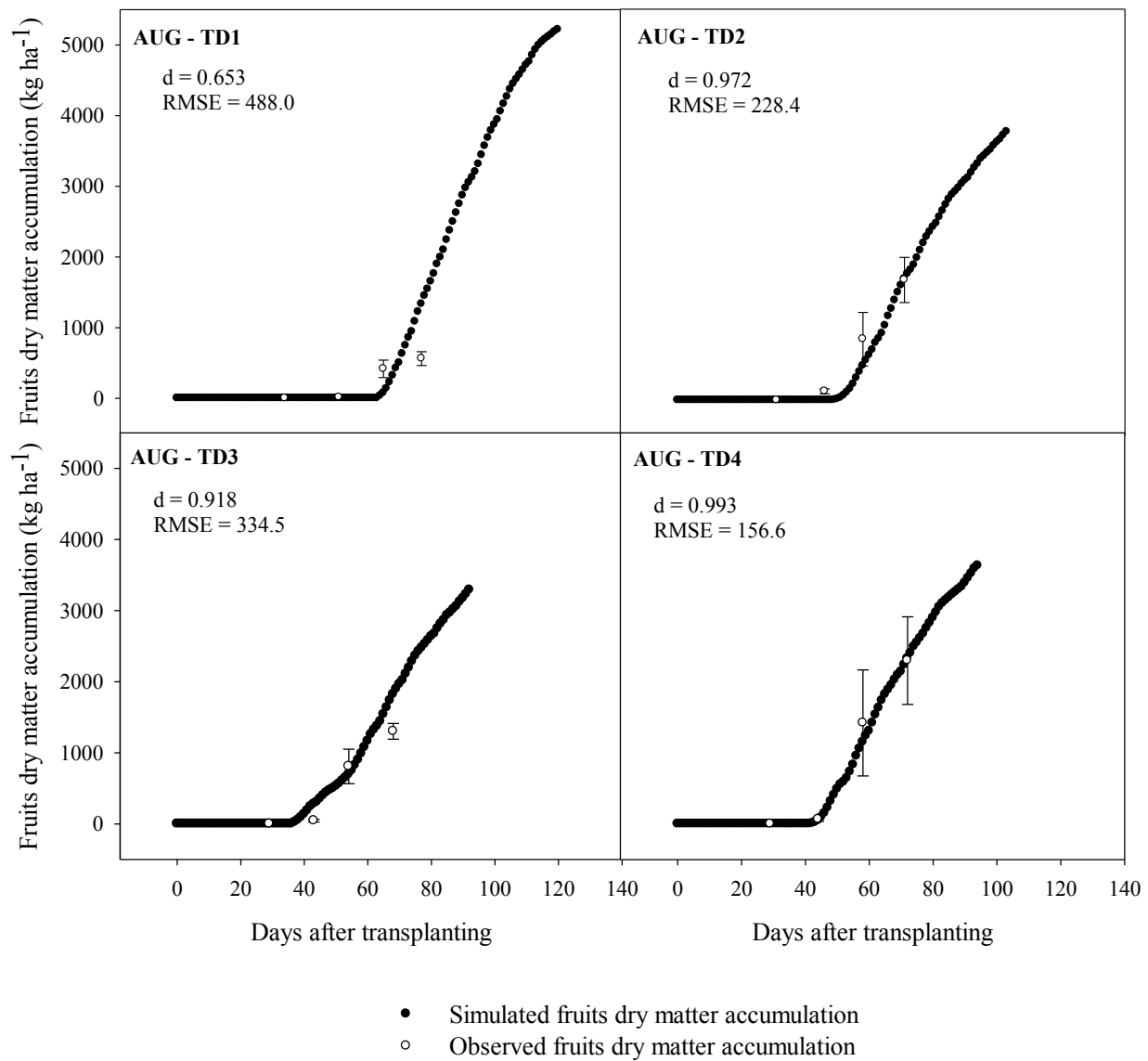


Figure 19: Simulated and observed fruits dry matter accumulation (FDM) for AUG processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

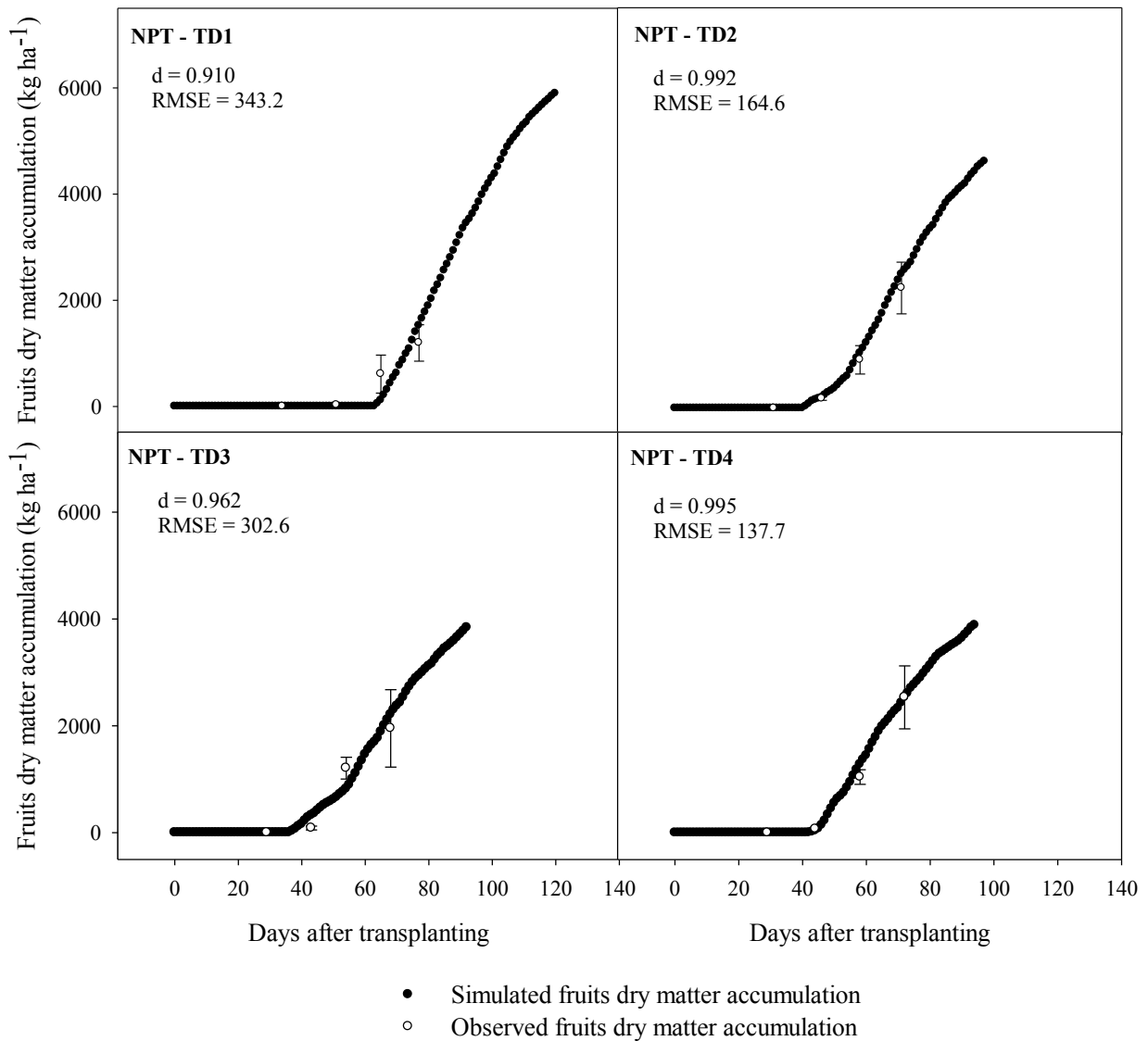


Figure 20: Simulated and observed fruits dry matter accumulation (FDM) for NPT processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

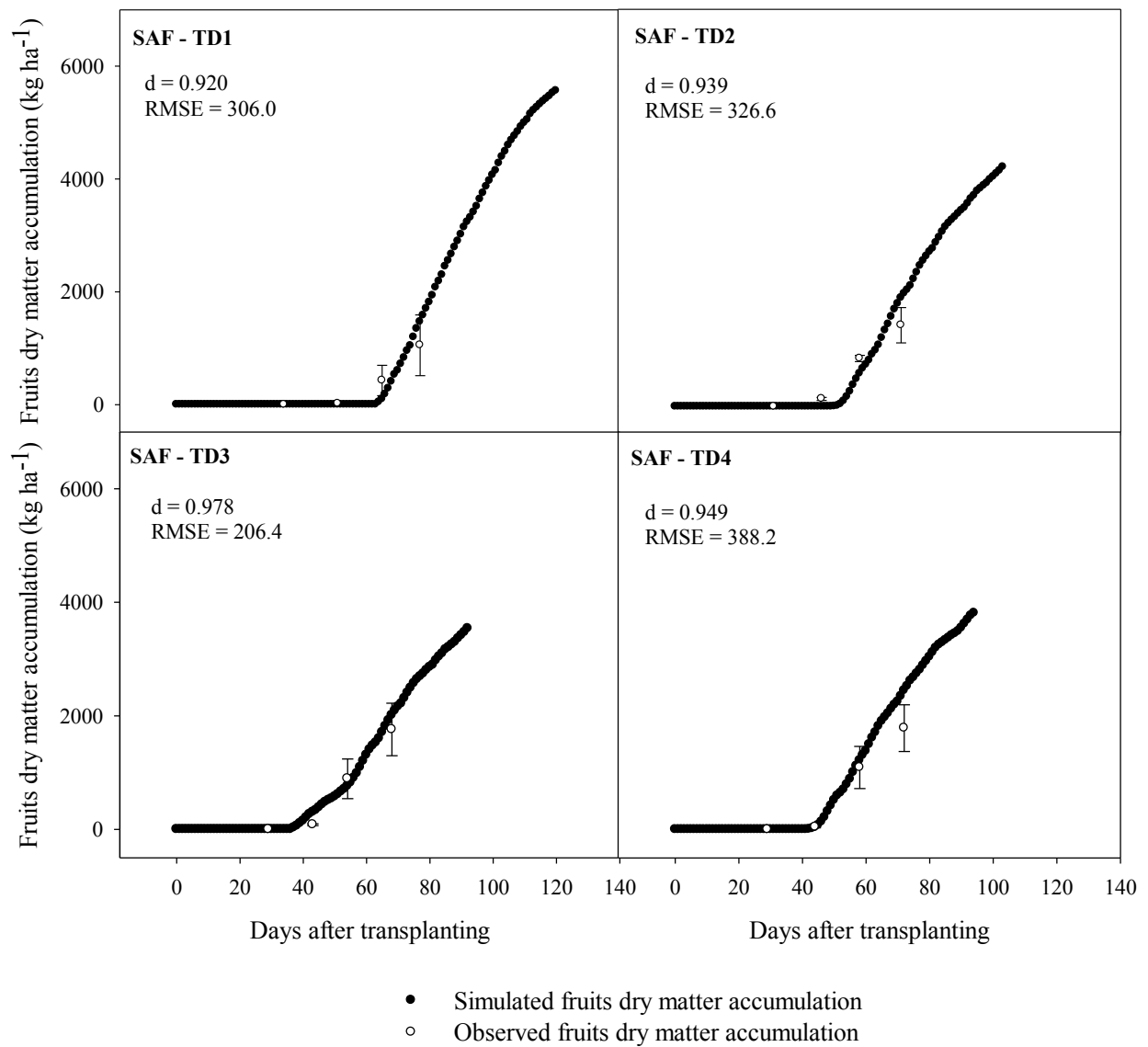


Figure 21: Simulated and observed fruits dry matter accumulation (FDM) for SAF processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

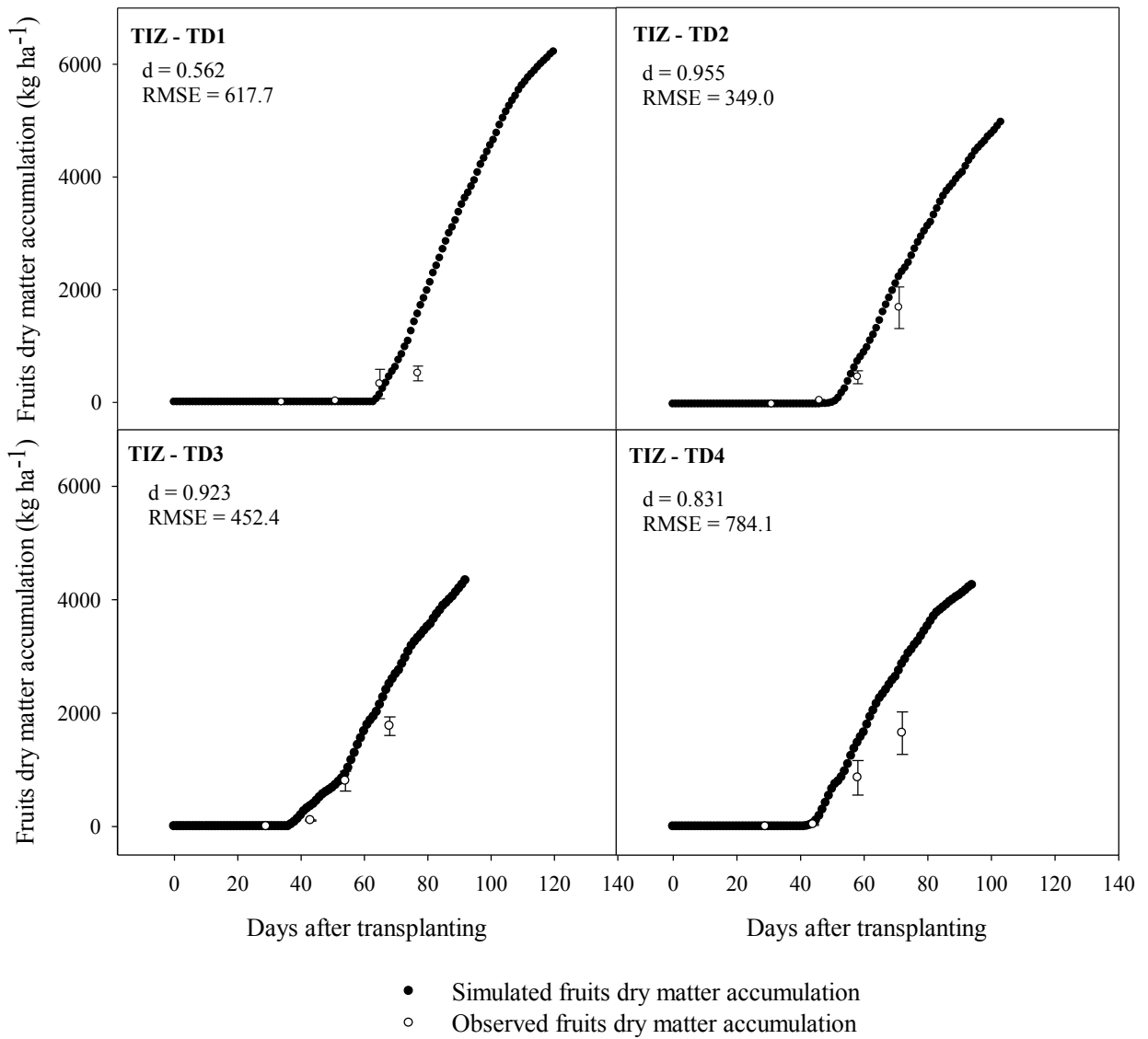


Figure 22: Simulated and observed fruits dry matter accumulation (FDM) for TIZ processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

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### 3.3.1.3. Fruits fresh weight accumulation

Fruits fresh weight is a new evaluating parameter was added in the 4.5 version of DSSAT model to evaluate the actual fresh yield of tomato plants. This parameter is affected by weather conditions, agronomic practices, and variety genetic characteristics. Figure 23 shows that fruit yield for AUG variety was well simulated by the model under TD2, 3 and 4; giving excellent values for d-Stat (0.938, 0.991 and 0.989, respectively) and relatively low RMSE values (8051, 2755 and 4163 kg ha<sup>-1</sup>, respectively). Simulation accuracy for yield at TD1 (0.725 for d-Stat, and 6713 kg ha<sup>-1</sup> for RMSE) was lower than the other transplanting dates, as model prediction is less effective at low air temperature. NPT variety had better simulation giving 0.898, 0.960, 0.937 and 0.998 as d-Stat values; and giving 5976.6, 9233.3, 10270.0 and 1619.7 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 24). SAF variety had also very good simulation, giving 0.944, 0.958 0.983 and 0.961 as d-Stat values; and giving 4218.1, 6556.5, 3640.5 and 6801.0 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 25). Plants of TIZ variety had an over simulation for TD1 and very good simulation for the other three transplanting dates giving 0.495, 0.986, 0.990 and 0.908 as d-Stat values; and giving 10674.1, 3831.7, 3556.8 and 11815.1 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 26). Having acceptable matches between observed and simulated yield even by changing the transplanting dates confirmed model ability to predict tomato plants development and yield under open field conditions.



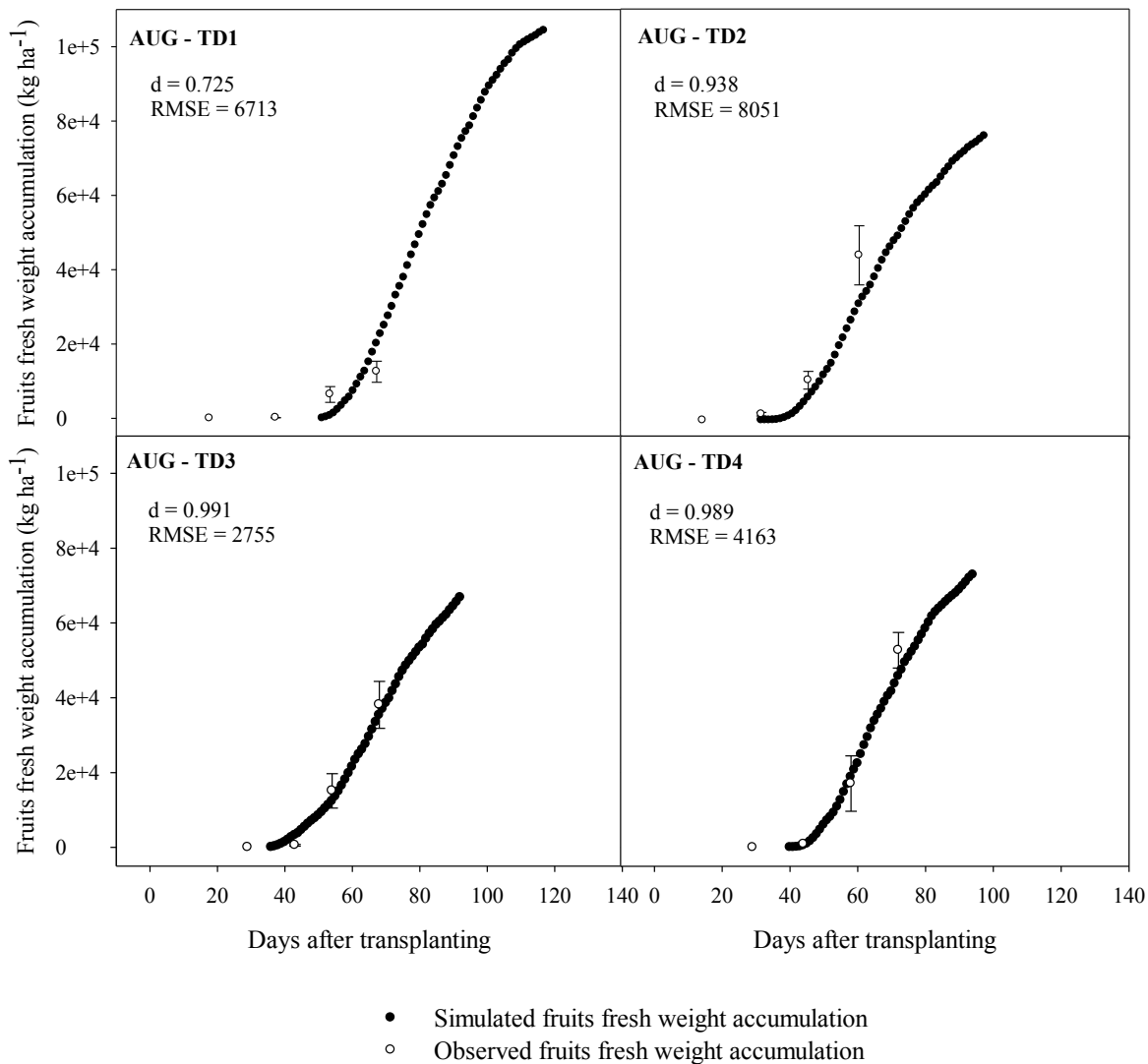


Figure 23: Simulated and observed fresh fruits weight accumulation (FFW) for AUG processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

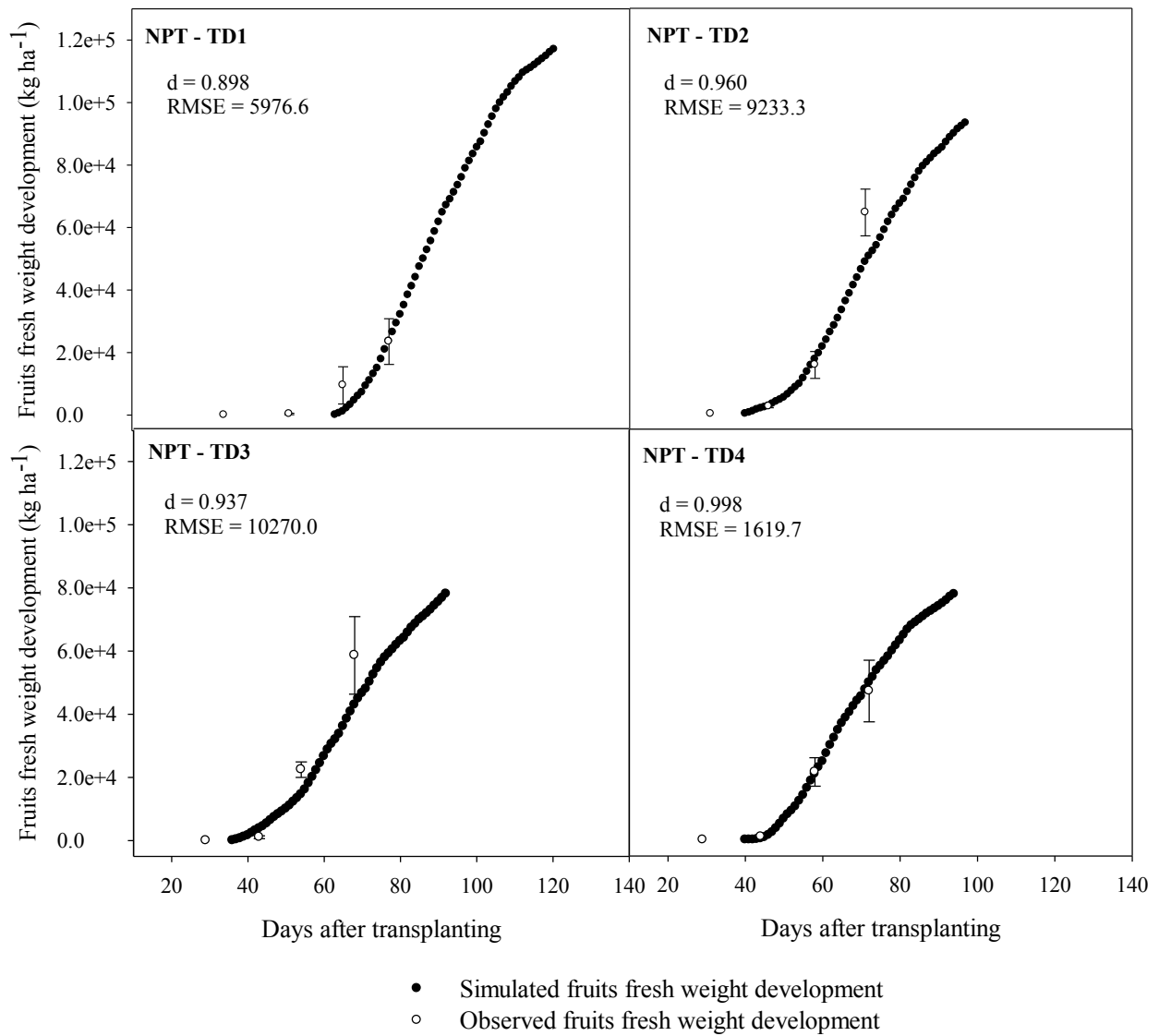


Figure 24: Simulated and observed fresh fruits weight accumulation (FFW) for NPT processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

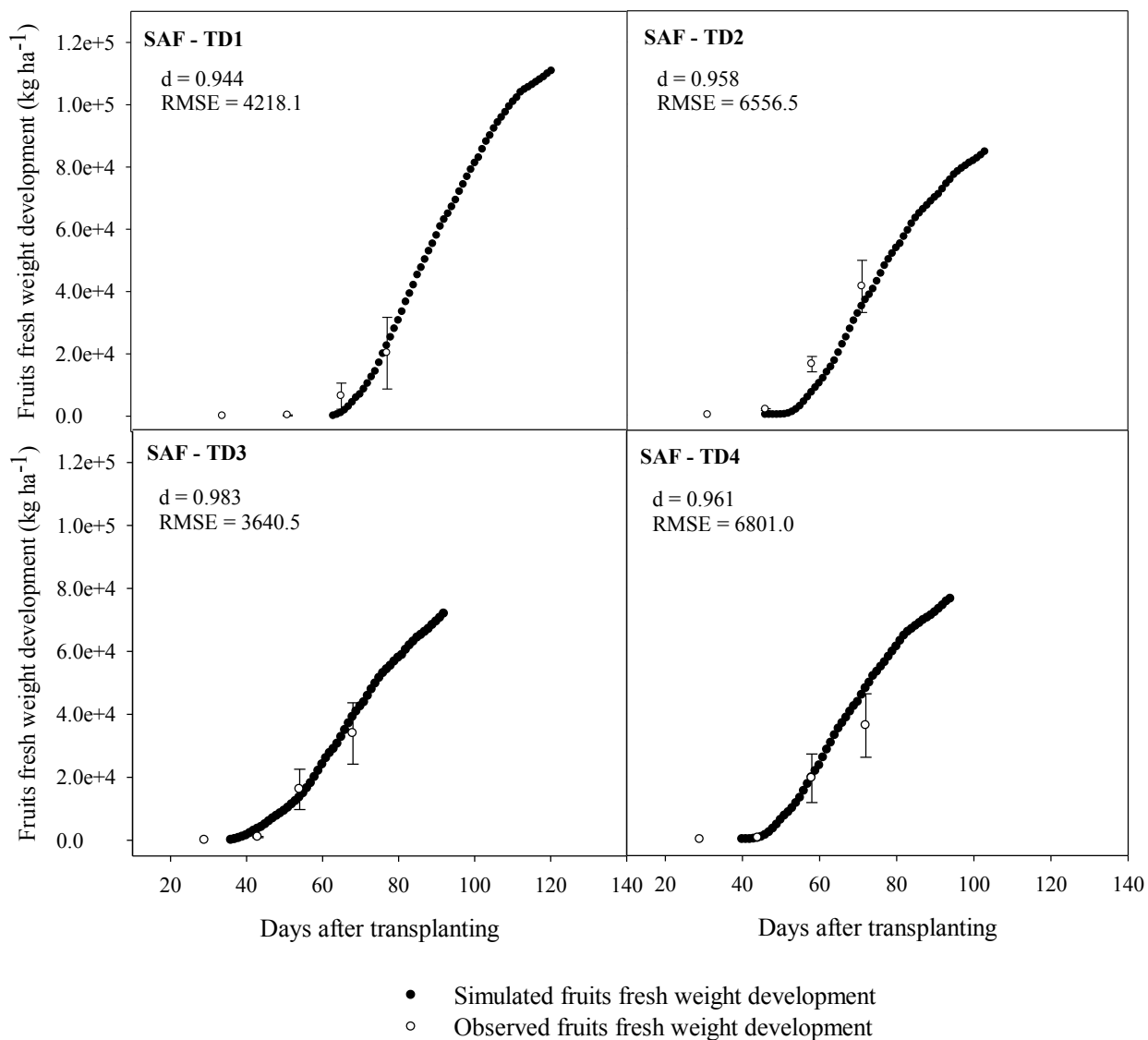


Figure 25: Simulated and observed fresh fruits weight accumulation (FFW) for SAF processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

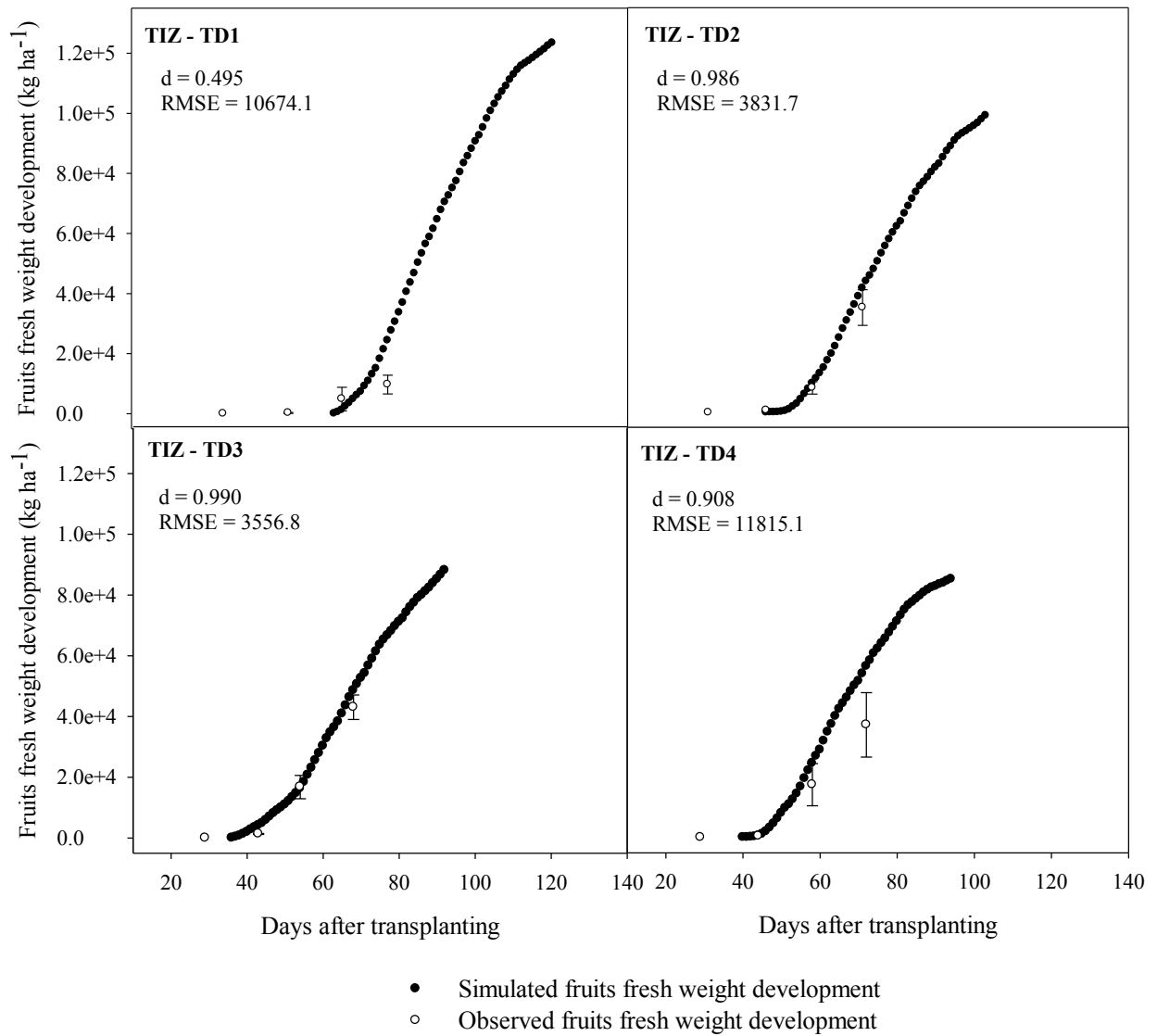
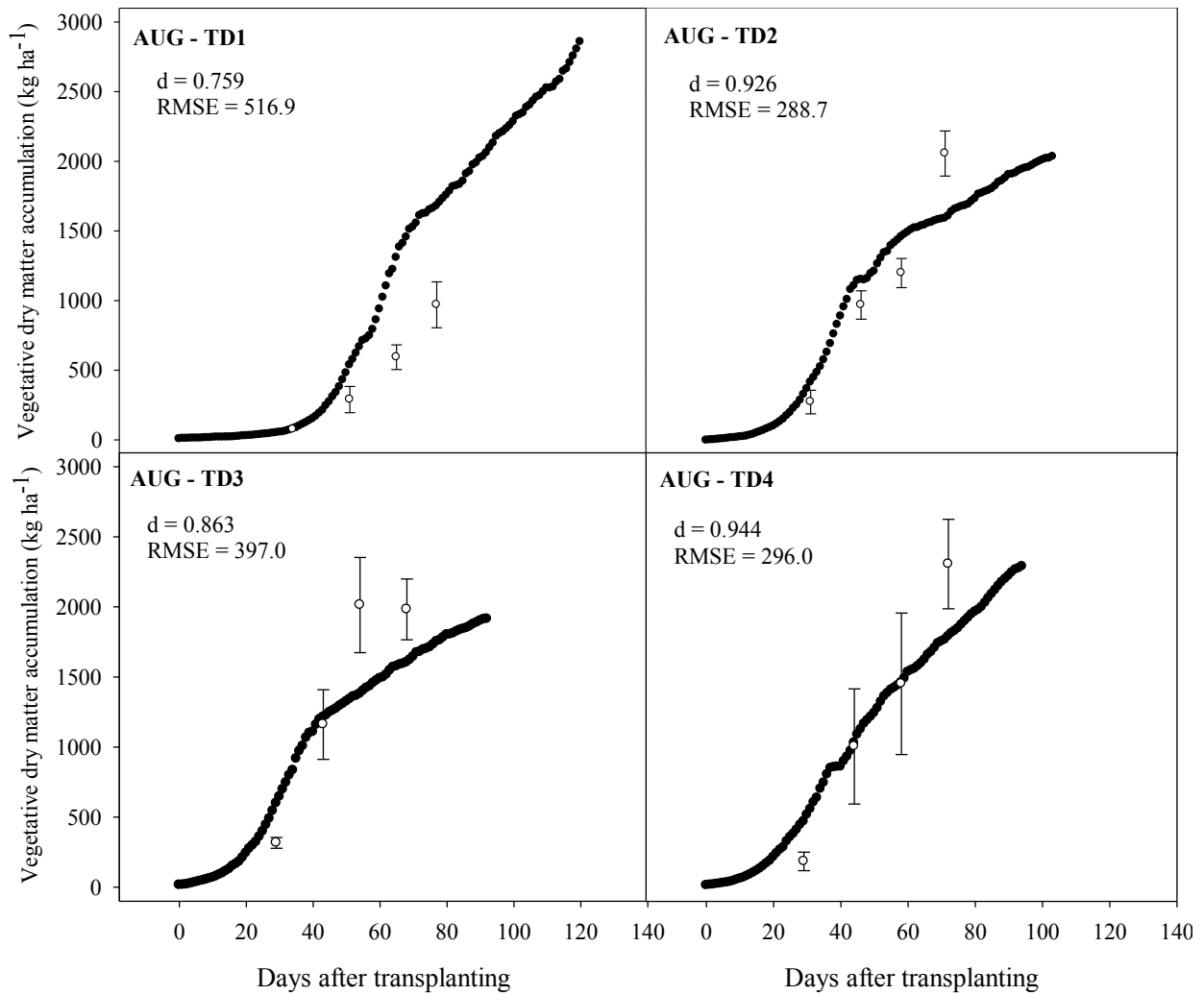


Figure 26: Simulated and observed fresh fruits weight accumulation (FFW) for TIZ processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

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#### 3.3.1.4. Vegetative dry matter accumulation

Figure 27 shows model simulation of the observed vegetative dry matter accumulation for AUG variety at different transplanting dates. Calibration indexes at the four transplanting dates showed good indications for d-Stat values (0.759, 0.926, 0.863 and 0.944, respectively) and low RMSE values (516.9, 288.7, 397 and 296 kg ha<sup>-1</sup>, respectively) with good simulation at the beginning of growing cycle then it was over simulation at the end of the growing cycle for TD1. NPT variety had similar simulation to AUG variety giving 0.780, 0.825, 0.765 and 0.909 as d-Stat values; and giving 652.2, 573.1, 665.4 and 393.5 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 28). SAF variety had also very good simulation, giving 0.879, 0.947 0.868 and 0.866 as d-Stat values; and giving 496.5, 272.1, 401.9 and 531.0 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 29). Plants of TIZ variety had an acceptable simulation for TD1 and very good simulation for the other three transplanting dates giving 0.635, 0.859, 0.792 and 0.956 as d-Stat values; and giving 984.9, 534.7, 679.3 and 280.8 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 30). Model was able to simulate vegetative growth evolution quite good when air temperature was more favorable for tomato plants.



- Simulated vegetative dry matter accumulation
- Observed vegetative dry matter accumulation

Figure 27: Simulated and observed vegetative dry matter accumulation (VDM) for AUG processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

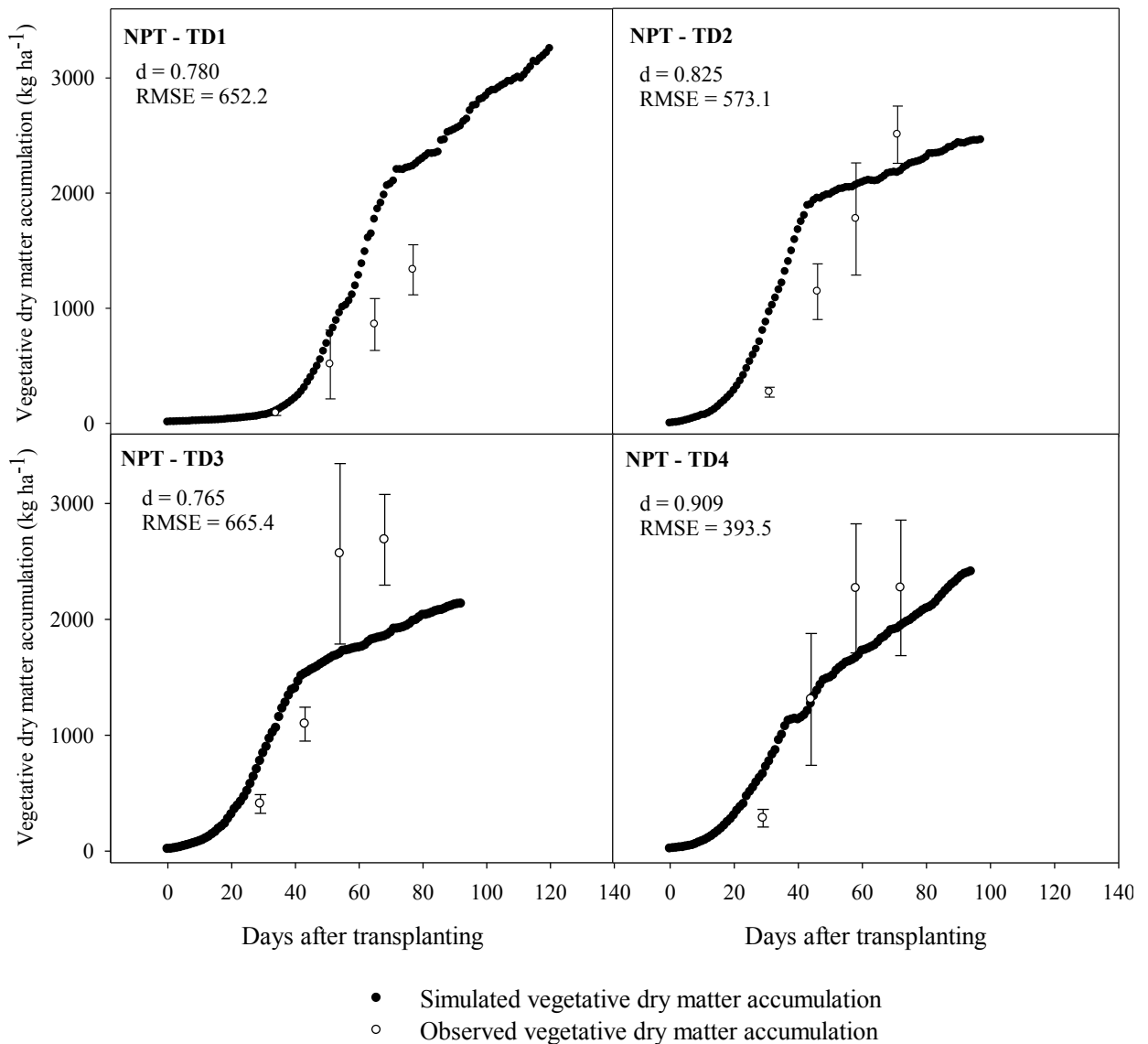


Figure 28: Simulated and observed vegetative dry matter accumulation (VDM) for NPT processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

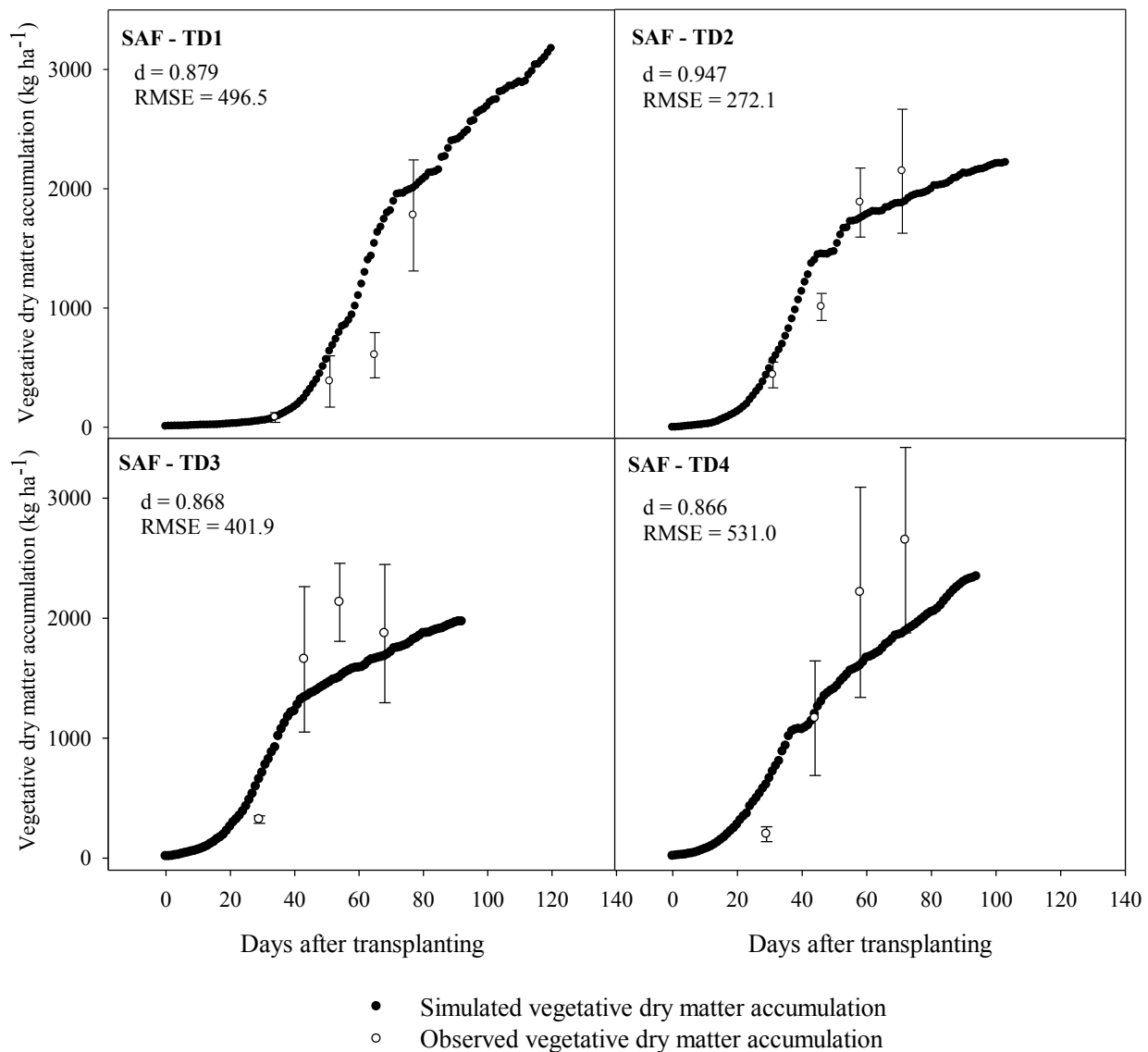


Figure 29: Simulated and observed vegetative dry matter accumulation (VDM) for SAF processing tomato variety at the four different transplanting dates during the spring 2009 growing season.



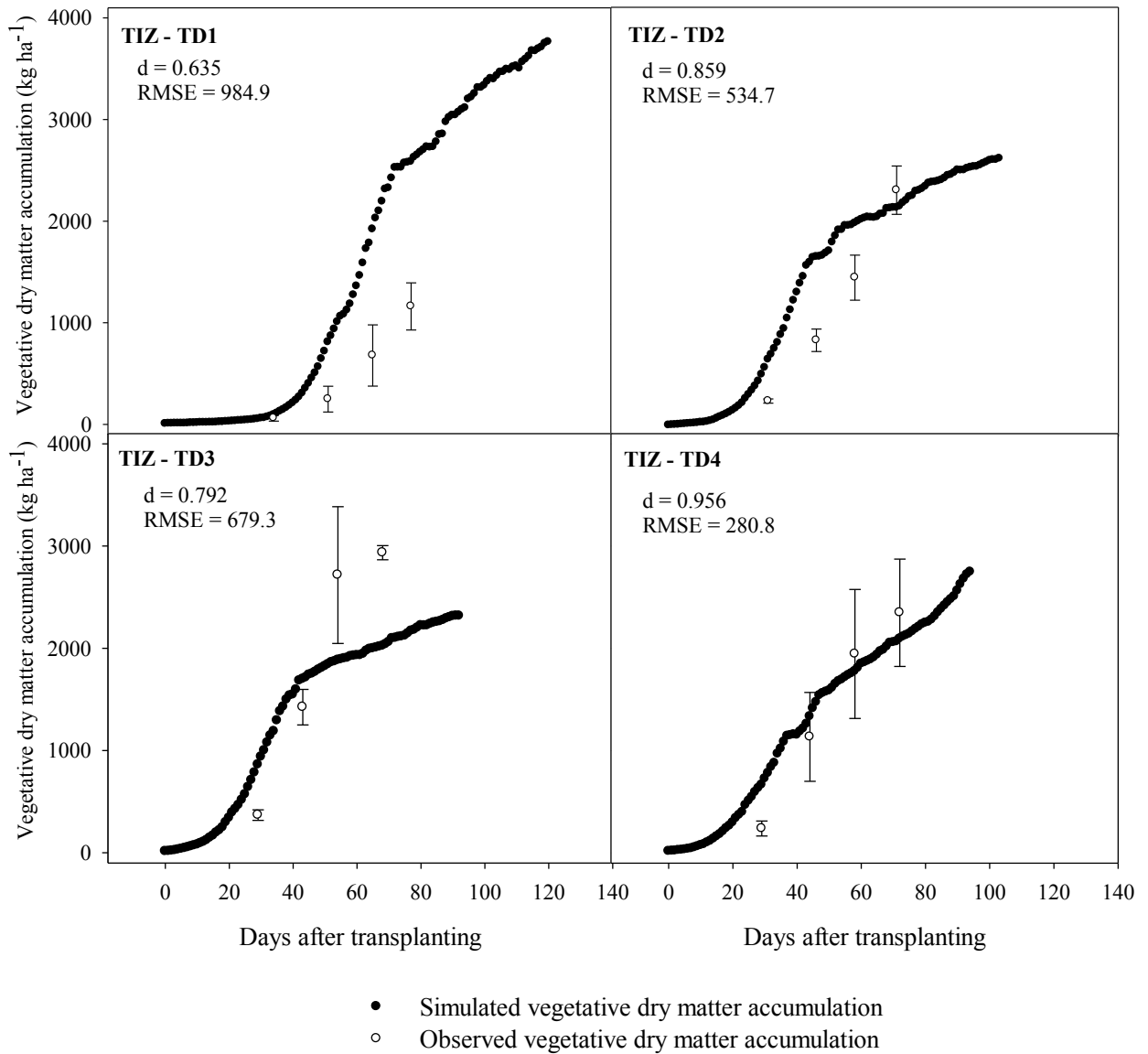


Figure 30: Simulated and observed vegetative dry matter accumulation (VDM) for TIZ processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

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### 3.3.1.5. . Number of fruits m<sup>-2</sup>

Evolution for number of fruits per m<sup>2</sup> was evaluated to see the match between its observed and simulated values. For AUG variety, model under TD1 and TD3 conditions gave relatively good simulation at the beginning of the growing cycle, whereas at the end of the growing cycle it gave over simulation (0.570 for d-Stat and 60 fruits m<sup>-2</sup> for RMSE) for TD1 and under simulation (0.670 for d-Stat and 48 fruits m<sup>-2</sup> for RMSE) for TD3 (Figure 31). The simulation of plants at TD2 and TD4 was good giving 0.928 and 0.913 d-Stat values, respectively; and 31 and 20 fruits m<sup>-2</sup> RMSE values, respectively. NPT variety had similar simulation to AUG variety giving 0.937, 0.780, 0.566 and 0.733 as d-Stat values; and giving 30, 59, 93 and 51 fruits m<sup>-2</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 32). SAF variety had good simulation, giving 0.739, 0.934 0.725 and 0.898 as d-Stat values; and giving 71, 34, 41 and 24 fruits m<sup>-2</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 33). Plants of TIZ variety had an over simulation for TD1 and TD3 and very good simulation for the TD2 and TD4 giving 0.564, 0.984, 0.628 and 0.913 as d-Stat values; and giving 48, 10, 51 and 17 fruits m<sup>-2</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 34).

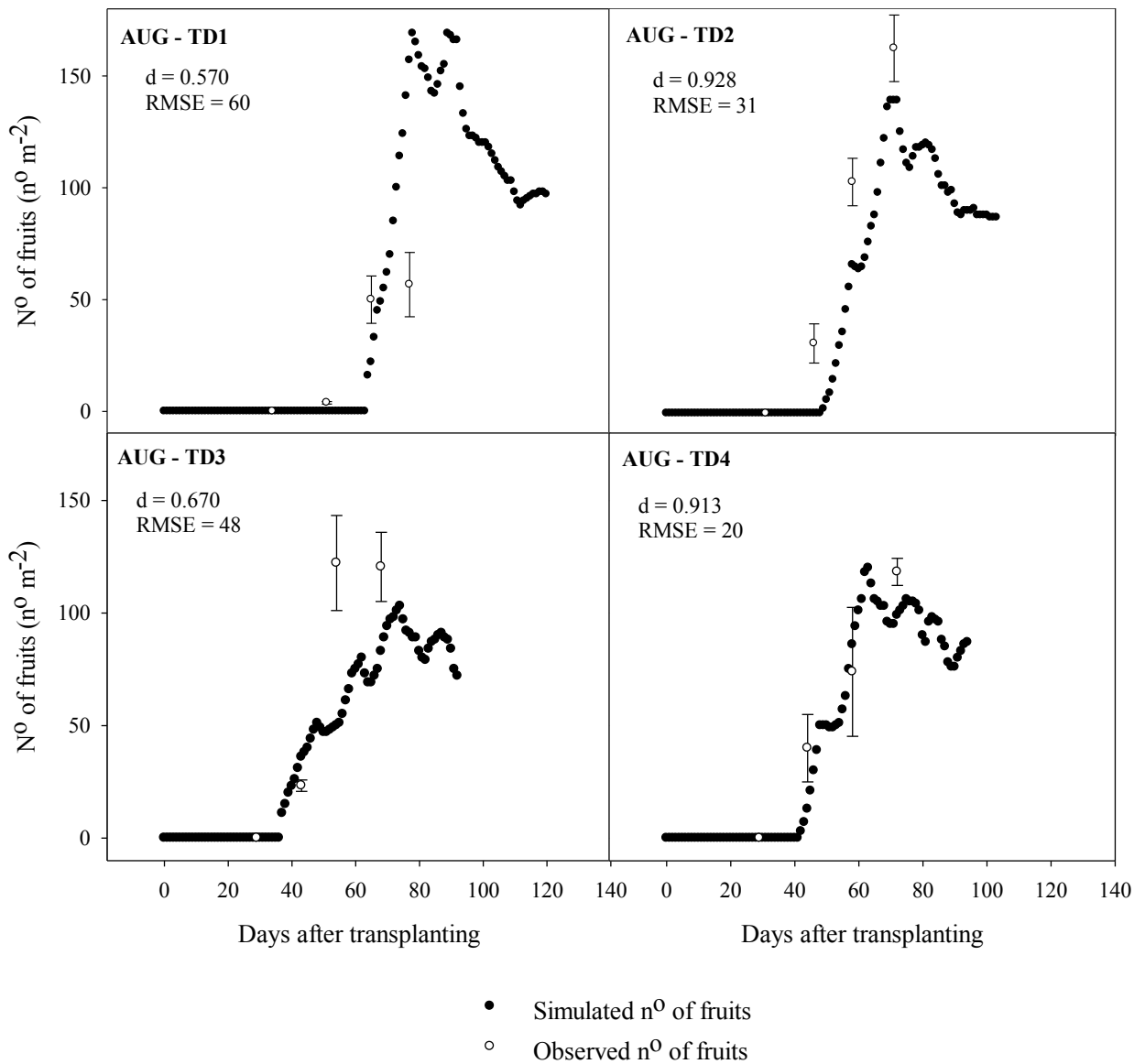


Figure 31: Simulated and observed number of fruits per  $m^2$  for AUG processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

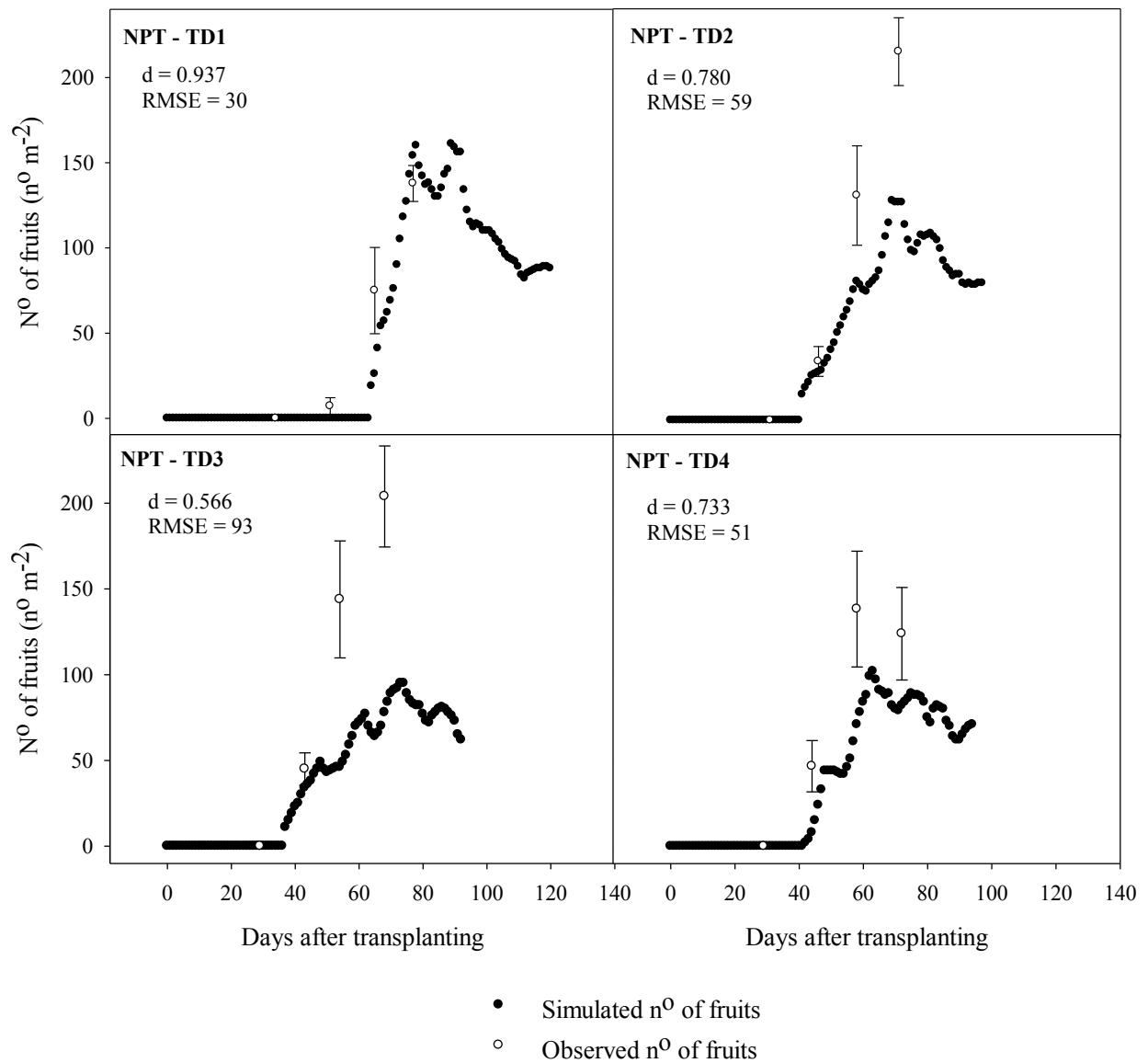


Figure 32: Simulated and observed number of fruits per  $\text{m}^2$  for NPT processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

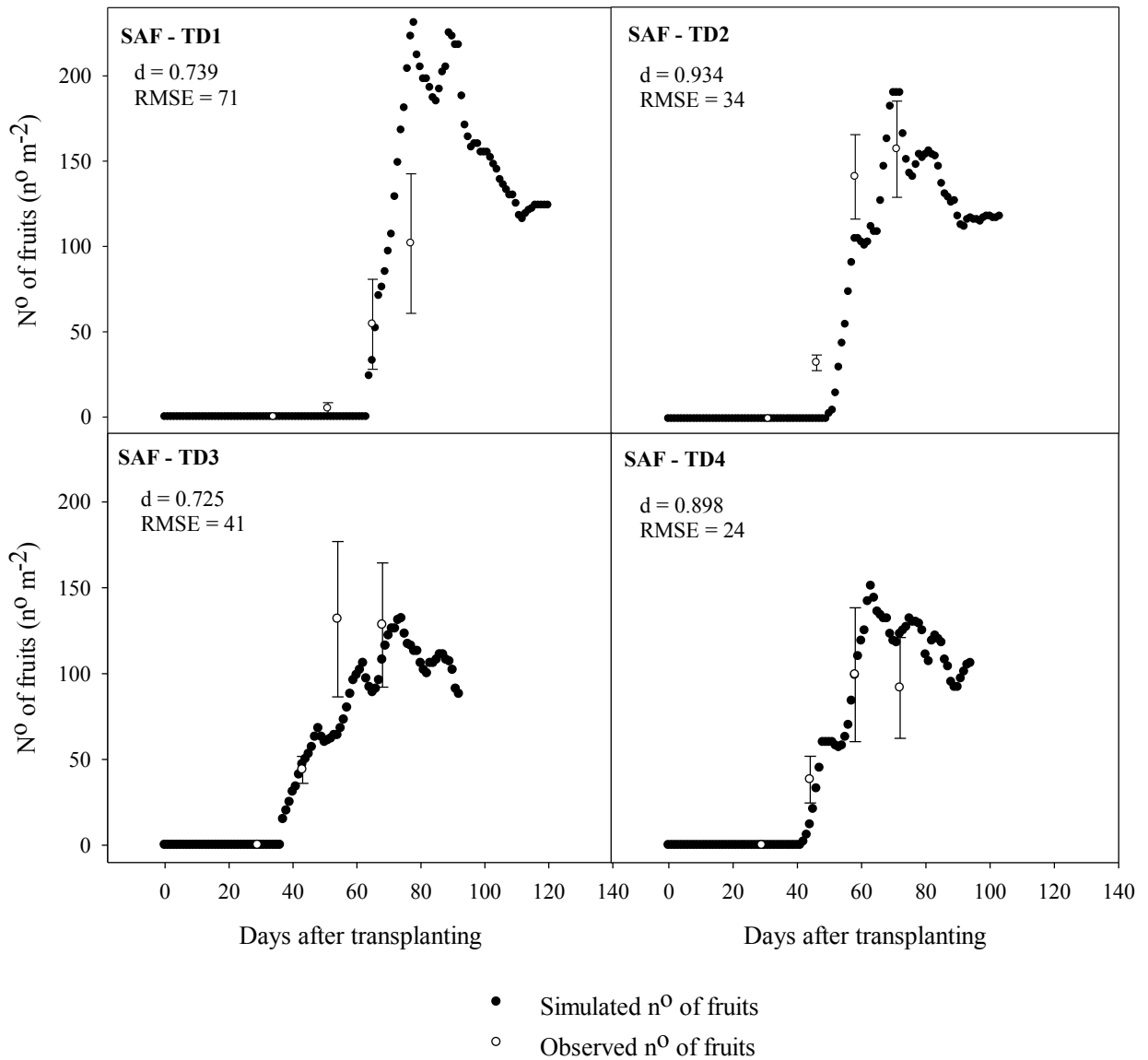


Figure 33: Simulated and observed number of fruits per  $m^2$  for SAF processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

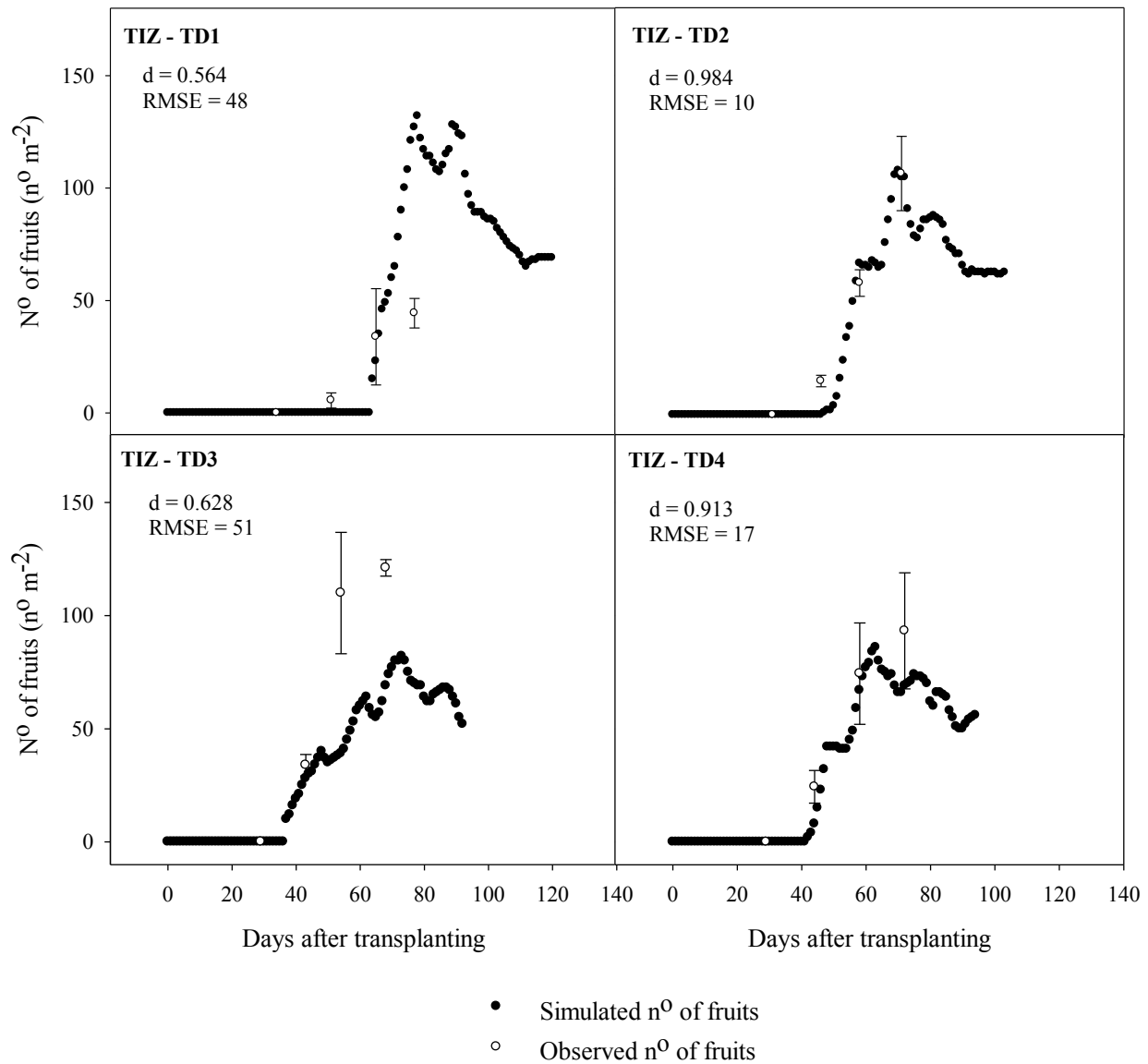


Figure 34: Simulated and observed number of fruits per  $m^2$  for TIZ processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

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### 3.3.1.6. Harvest index

Evaluation of plants harvest index over time was done in order to see model performance at different transplanting dates (Figure 35). Comparing observed and simulated evolution for AUG variety showed that TD2, 3 and 4 were well fitted giving d-Stat values of 0.913, 0.847 and 0.985, respectively; Whereas RMSE for them was 0.10, 0.12 and 0.05, respectively. For TD1, the agreement between observed and simulated evolution for harvest index was lower giving 0.702 for d-Stat and 0.20 for RMSE indices. Low temperature at the early transplanting caused late prediction for the rise of harvest index. NPT variety had similar simulation to AUG variety giving 0.799, 0.972, 0.882 and 0.977 as d-Stat values; and giving 0.18, 0.05, 0.10 and 0.06 as RMSE values for TD1, 2, 3 and 4, respectively (Figure 36). SAF variety had good simulation, giving 0.750, 0.915 0.940 and 0.939 as d-Stat values; and giving 0.17, 0.10, 0.08 and 0.10 as RMSE values for TD1, 2, 3 and 4, respectively (Figure 37). Plants of TIZ variety had an over simulation for TD1 and very good simulation for the other three transplanting dates giving 0.711, 0.959, 0.901 and 0.913 as d-Stat values; and giving 0.13, 0.07, 0.13 and 0.13 as RMSE values for TD1, 2, 3 and 4, respectively (Figure 38).

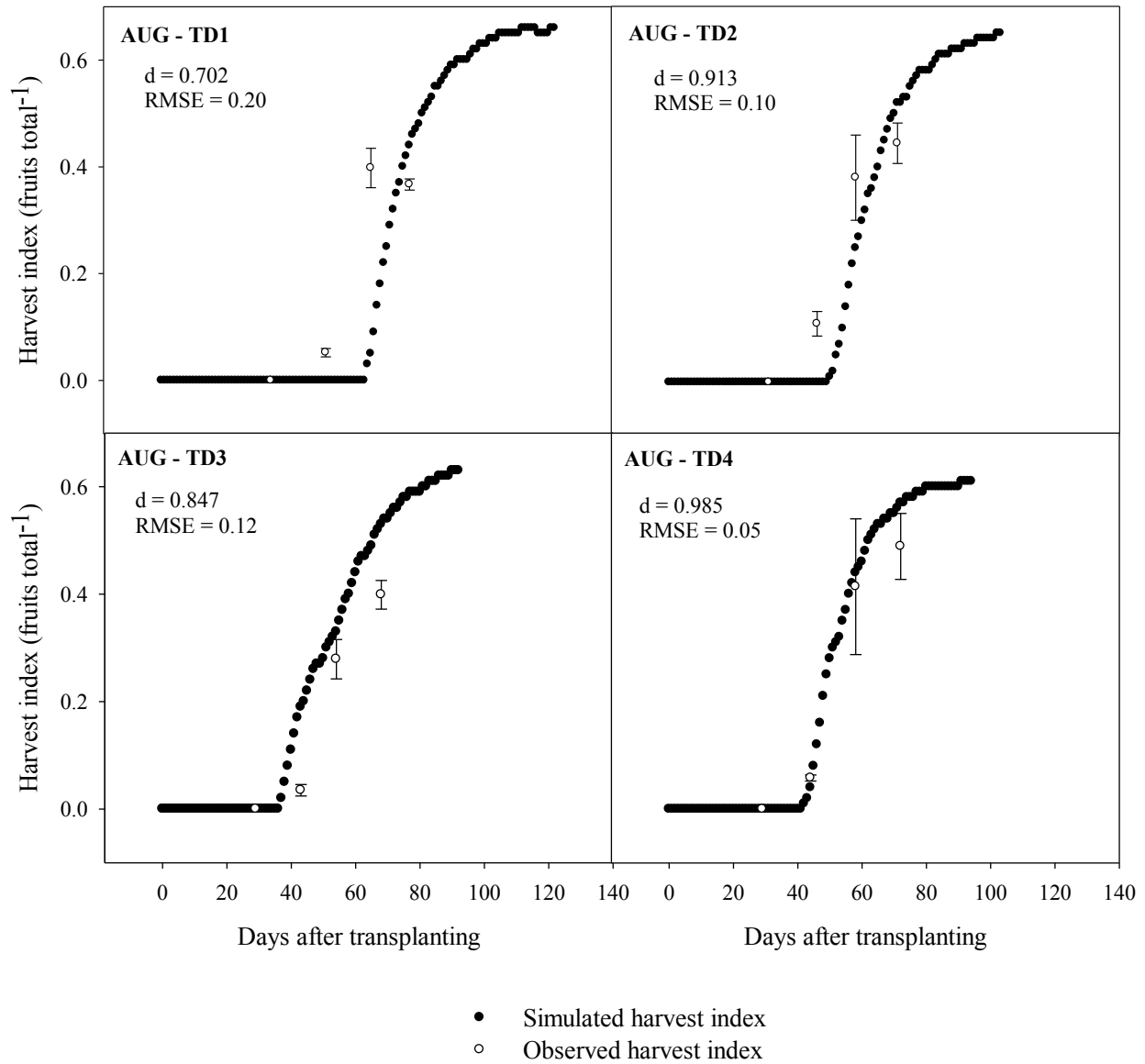


Figure 35: Simulated and observed harvest index (HI) for AUG processing tomato variety at the four different transplanting dates during the spring 2009 growing season.



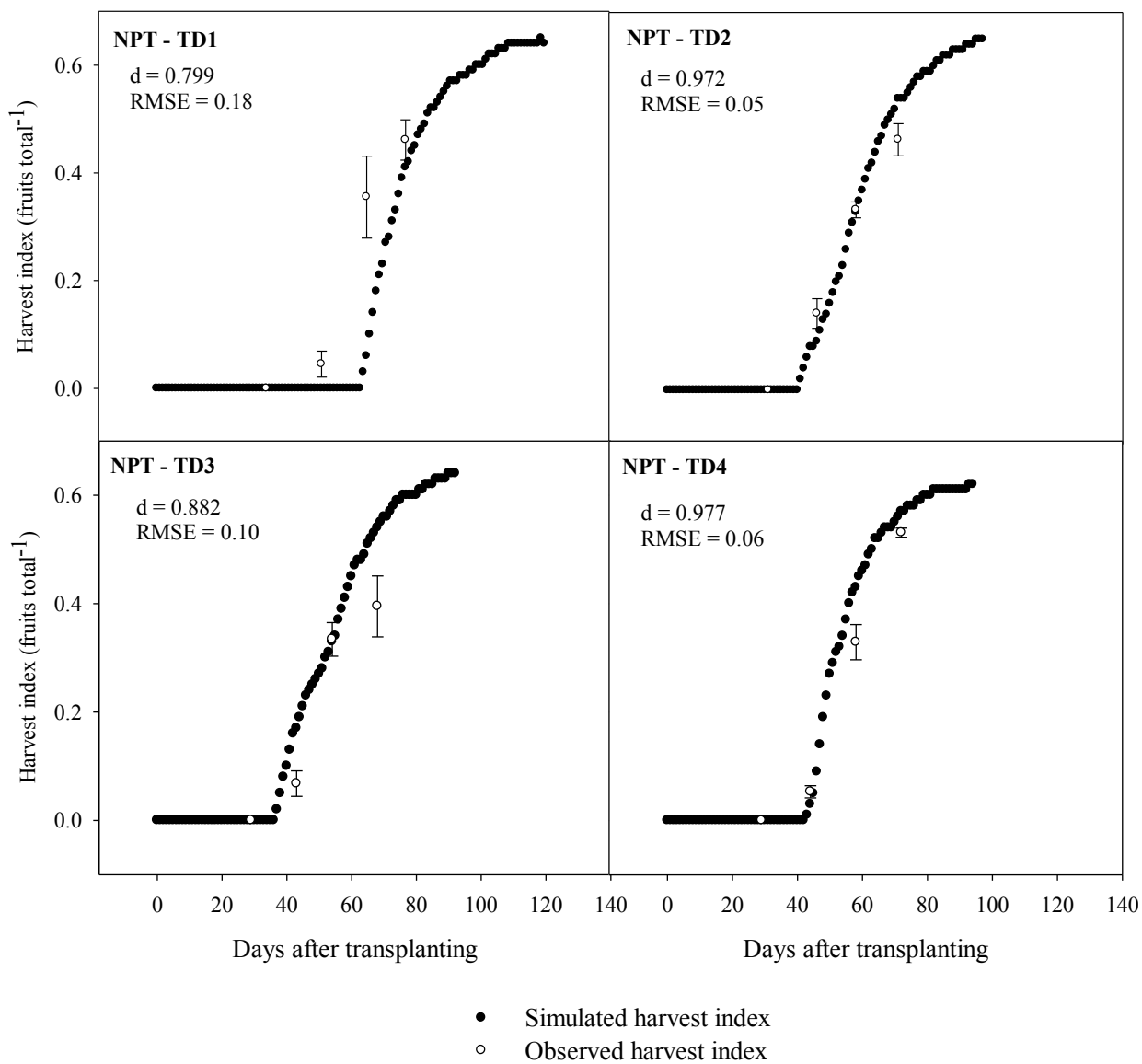


Figure 36: Simulated and observed harvest index (HI) for NPT processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

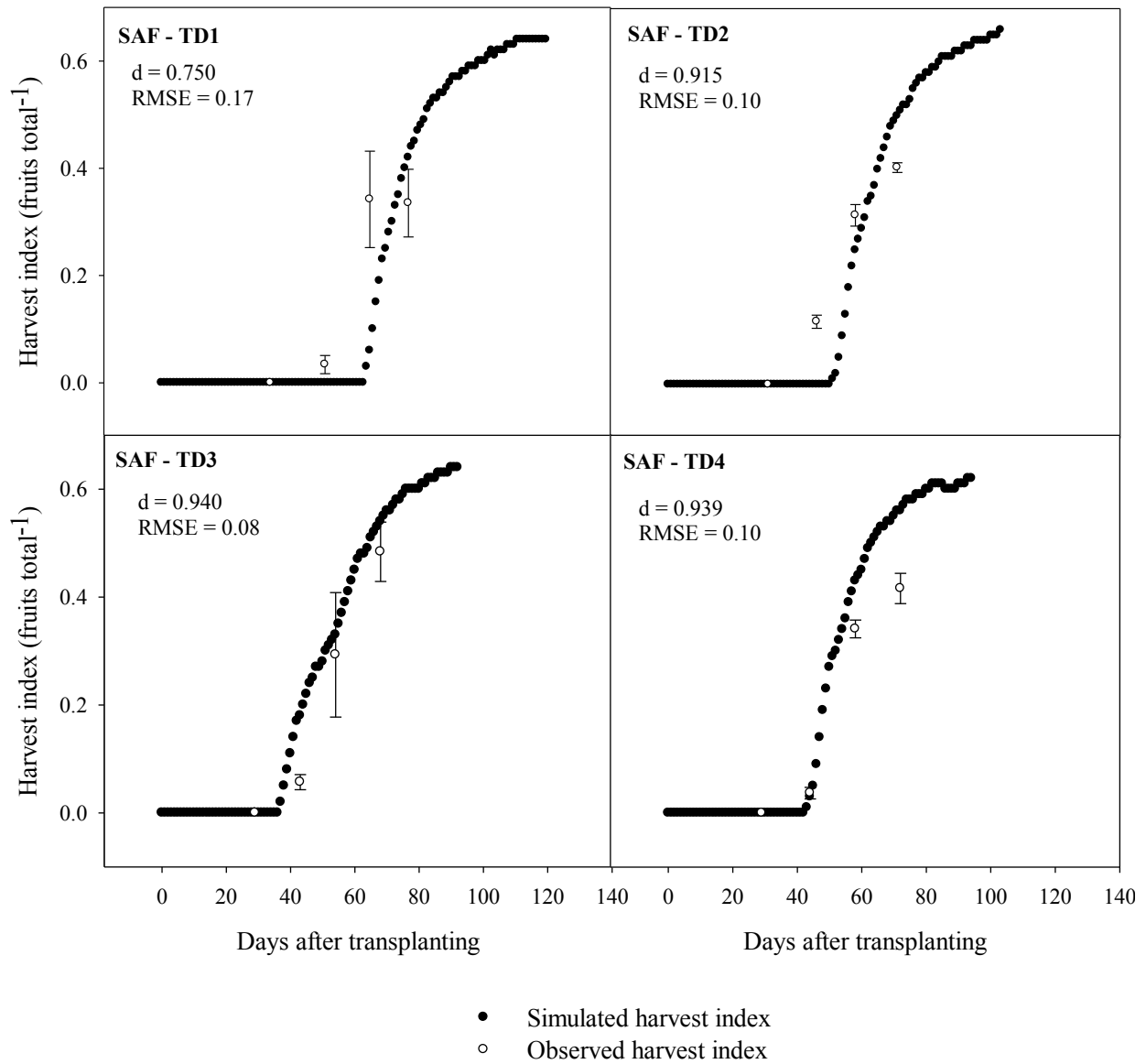


Figure 37: Simulated and observed harvest index (HI) for SAF processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

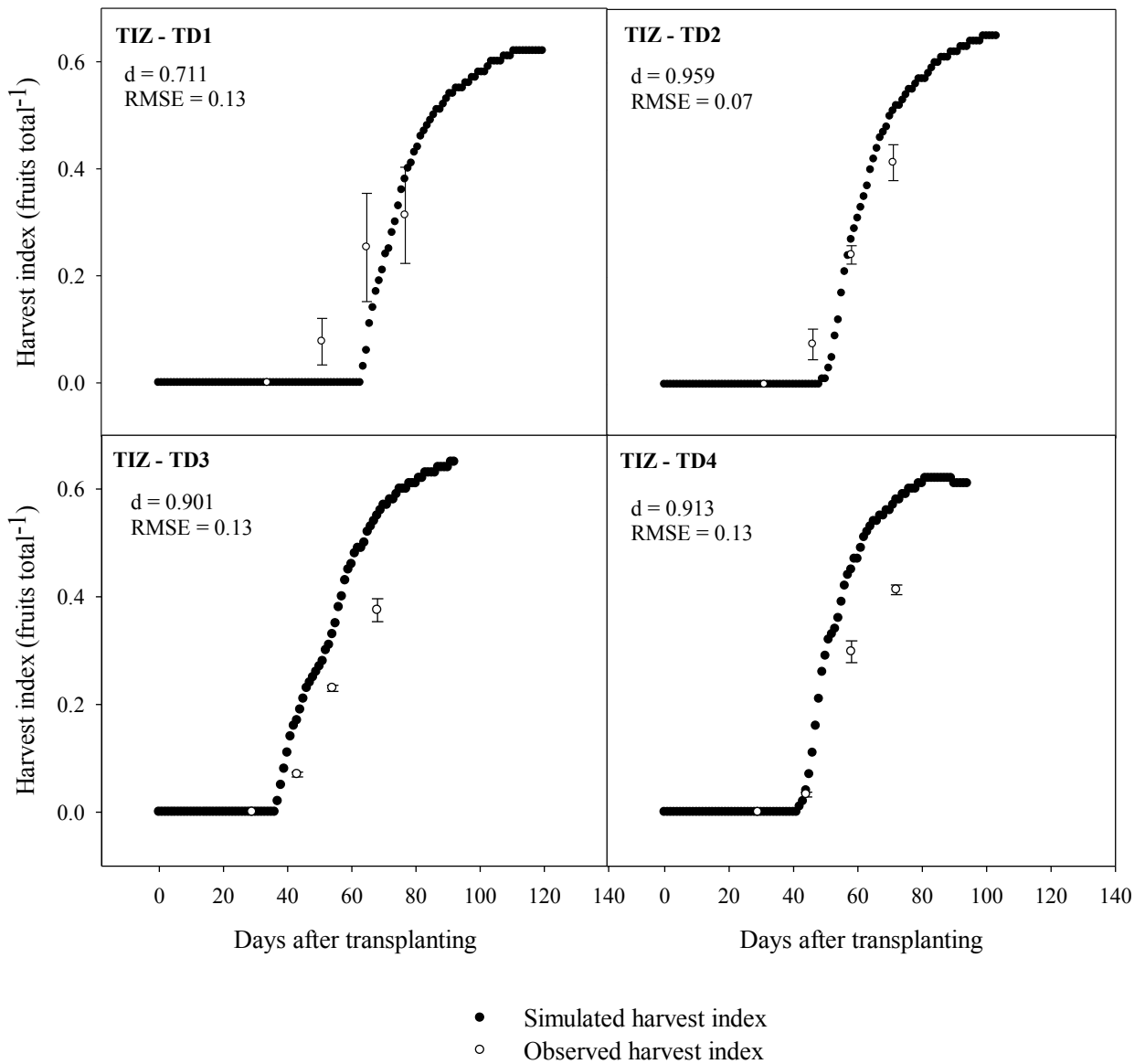


Figure 38: Simulated and observed harvest index (HI) for TIZ processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

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### 3.3.1.7. Leaf area index

Simulation of leaf area index using CSM-CROPGRO-Tomato model was relatively low compared to the other growth parameters (Figure 39). For AUG variety, it was well simulated under TD1 conditions (0.922 of d-Stat, and 0.14 of RMSE), whereas it gave unsatisfied under simulation for TD2, 3 and 4, giving d-Stat values of 0.592, 0.479 and 0.768, respectively; and RMSE values of 0.50, 0.73 and 0.21, respectively. NPT variety had similar simulation to AUG variety giving 0.924, 0.524, 0.511 and 0.584 as d-Stat values; and giving 0.17, 0.64, 0.76 and 0.52 as RMSE values for TD1, 2, 3 and 4, respectively (Figure 40). SAF variety had under simulation, giving 0.785, 0.600 0.501 and 0.616 as d-Stat values; and giving 0.32, 0.50, 0.84 and 0.51 as RMSE values for TD1, 2, 3 and 4, respectively (Figure 41). Plants of TIZ variety had an over simulation for TD1 and under simulation for the other three transplanting dates giving 0.740, 0.609, 0.511 and 0.717 as d-Stat values; and giving 0.35, 0.33, 0.82 and 0.28 as RMSE values for TD1, 2, 3 and 4, respectively (Figure 42).

Simulated LAI fitted the measured data during initial growth as shown by a slow increasing of LAI due to the transplant shock coupled with the crop being source limited due to incomplete light interception. Thereafter, the fit was less perfect possibly due to large variability in the observed data. These results were in accordance with Scholberg *et al.* (1997) who is the developer of CSM-CROPGRO-Tomato for open field conditions. They were also in accordance with Rinaldi *et al.* (2007) findings who found that simulated LAI increased slower than measured ones probably because the model does not take into account the twin rows plant distribution and overestimates the competition for light among plants.

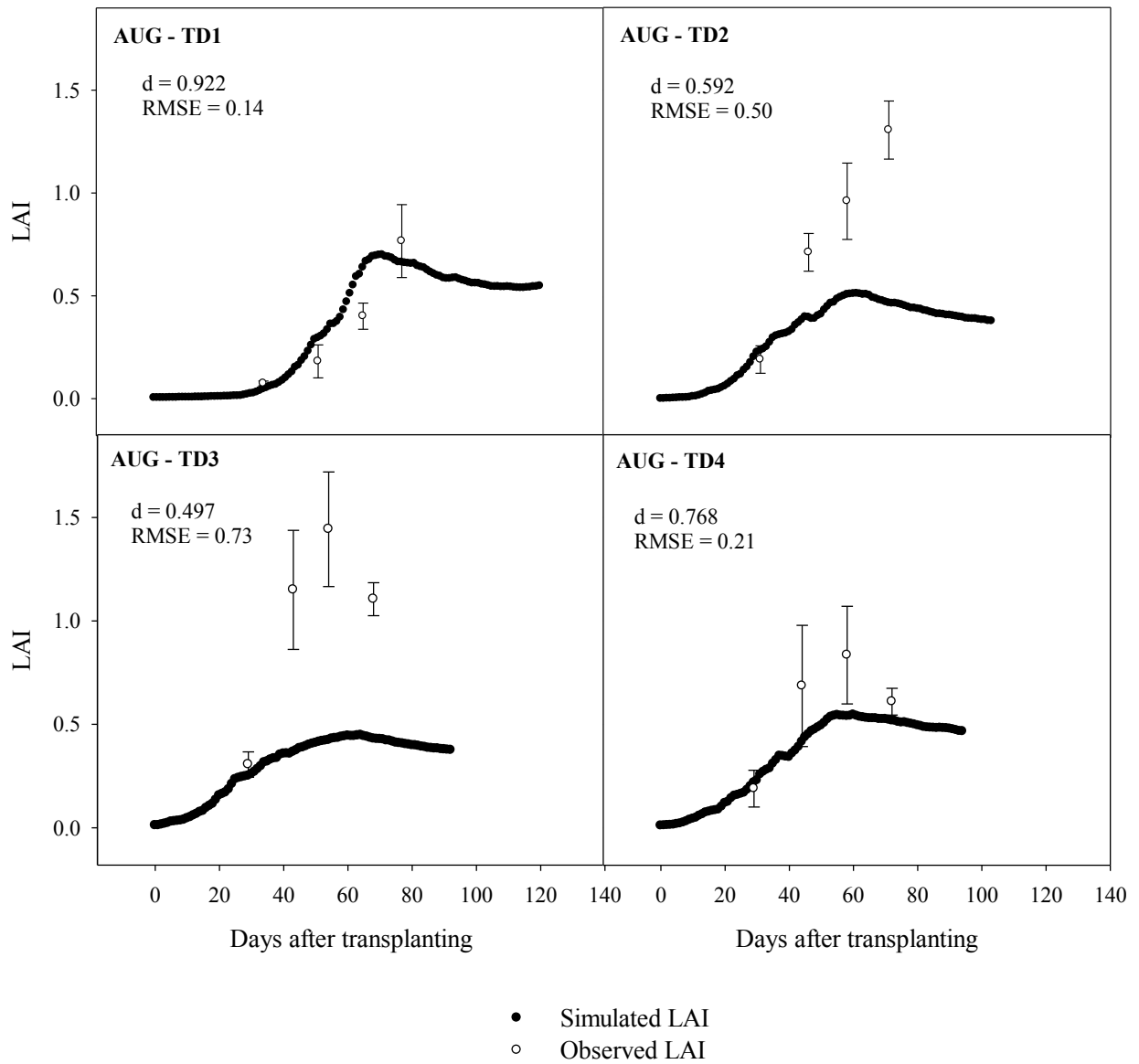


Figure 39: Simulated and observed leaf area index (LAI) for AUG processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

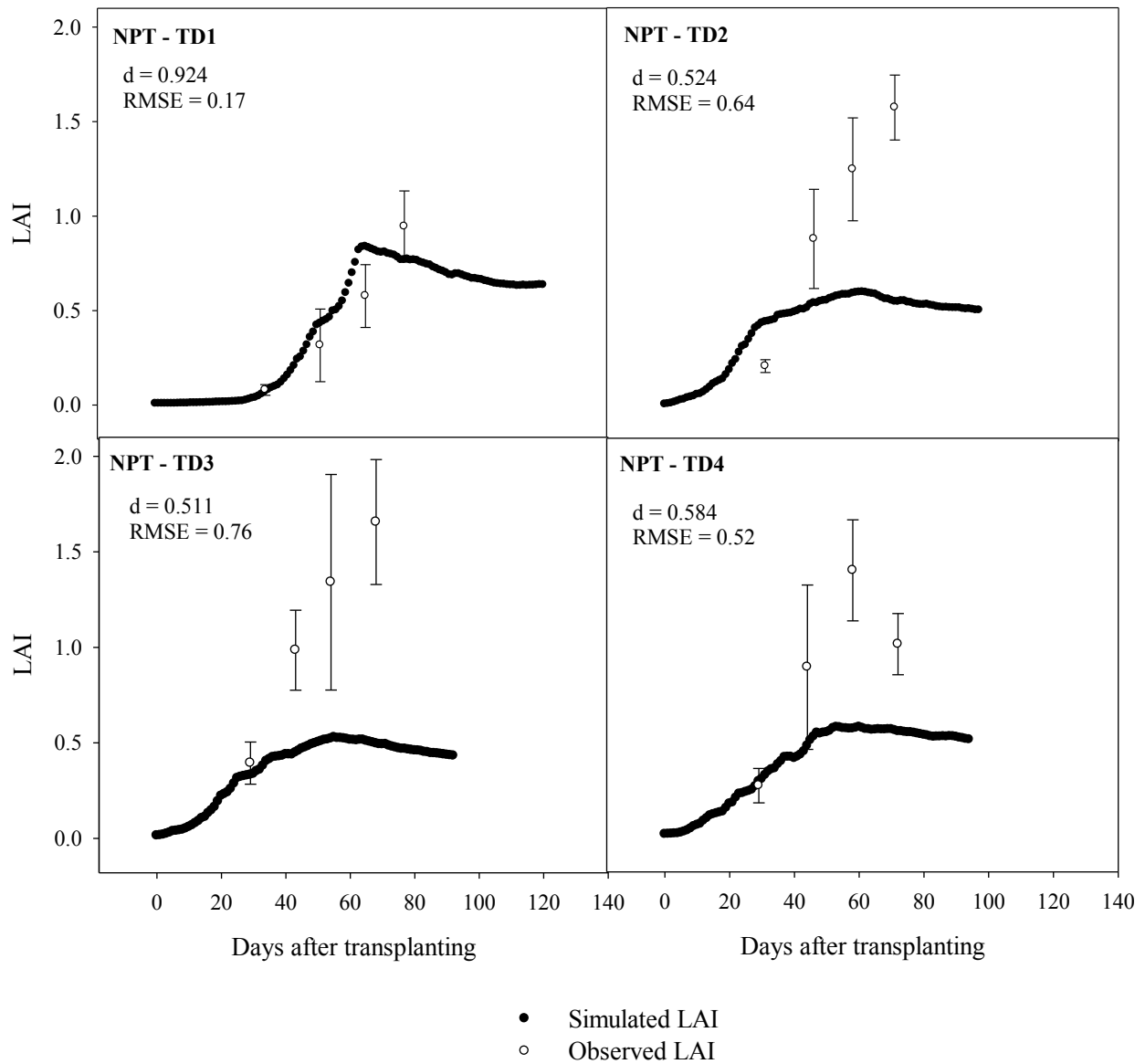


Figure 40: Simulated and observed leaf area index (LAI) for NPT processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

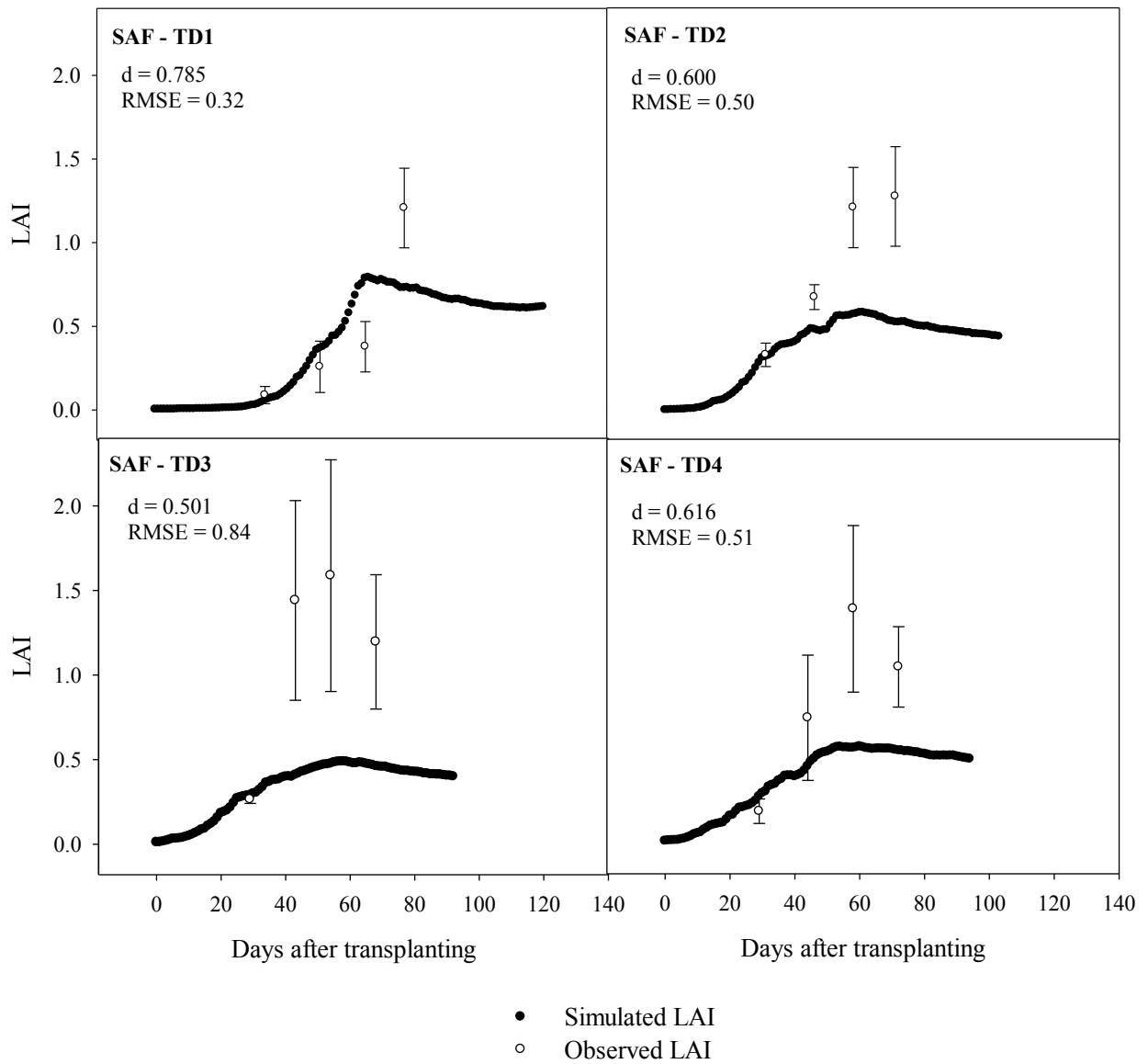


Figure 41: Simulated and observed leaf area index (LAI) for SAF processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

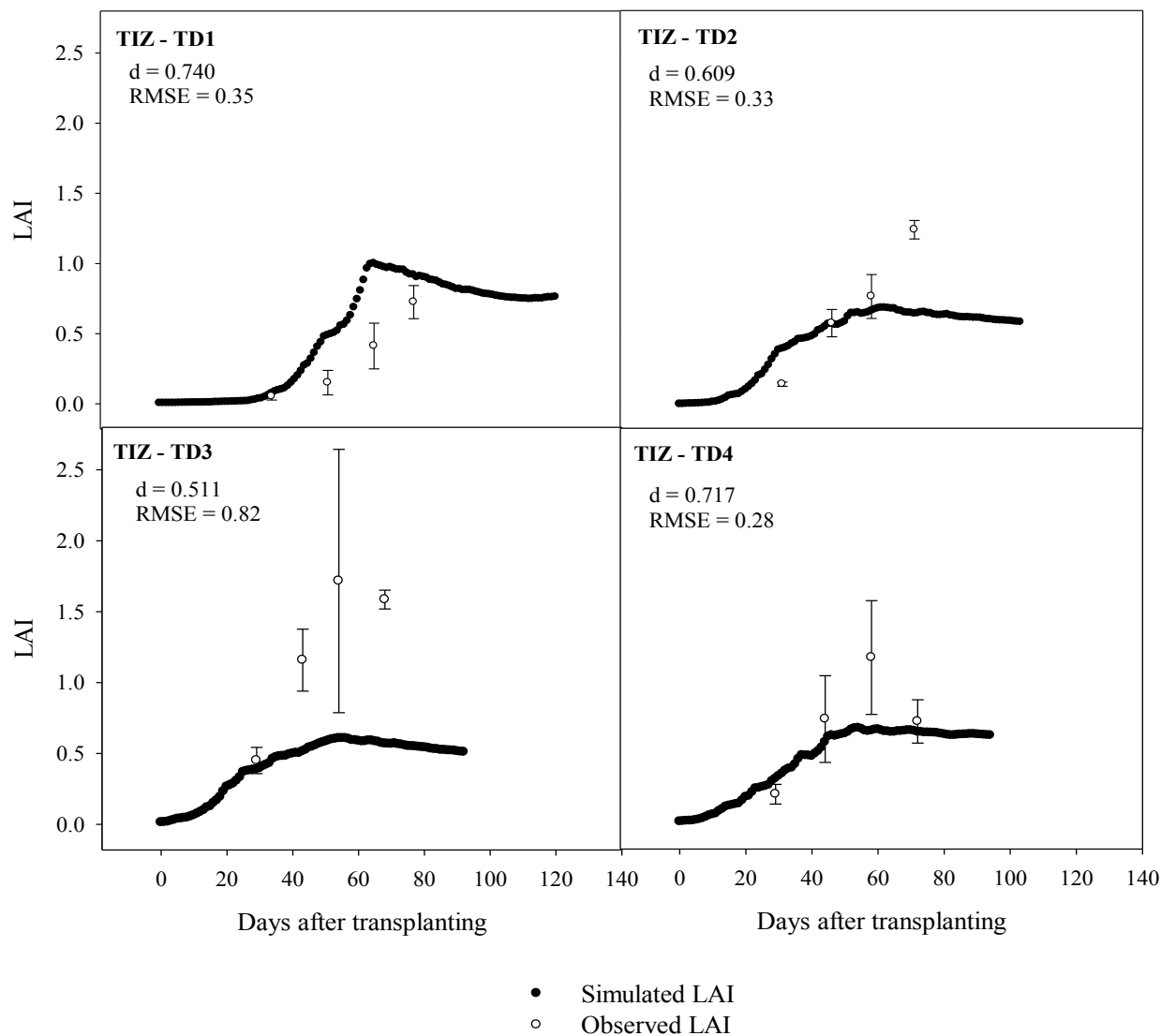


Figure 42: Simulated and observed leaf area index (LAI) for TIZ processing tomato variety at the four different transplanting dates during the spring 2009 growing season.

### 3.3.1.8. Final remarks

Calibration process resulted in: model efficiently simulated total plant dry matter, fruits fresh and dry weight, and harvest index; then it acceptably simulated vegetative dry weight and number of fruits, while it poorly simulated leaf area index of field-grown processing tomato for the four varieties under study. First transplanting date had low simulation efficiency compared to other transplanting dates.



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### 3.3.2. Validation of CSM-CROPGRO-Tomato model

#### 3.3.2.1. Total dry matter accumulation

In the four sampling dates was taken during field experiment period, accumulation of the above ground part of tomato plants was measured as parameters to validate the performance of CSM-CROPGRO-Tomato model. For the two varieties used in spring 2010 growing season, we were able to arrive to acceptable matching levels between observed values from the field and model simulation values. The main statistical indices used to evaluate the accuracy of the model are reported.

Comparing the simulated vs. observed values for total dry matter accumulation of Augusto F1 plants we found that model d-Stat values between simulated and observed values for AUG variety at the first three transplanting dates were 0.931, 0.950 and 0.931, respectively; and RMSE values at them were 1239, 1045 and 1325 kg ha<sup>-1</sup>, respectively (Figure 43). At TD4, simulation was over than the observed values especially at the end of the growing cycle (0.626 of d-Stat and 2494 kg ha<sup>-1</sup> of RMSE). NPT variety had similar simulation to AUG variety giving 0.947, 0.987, 0.959 and 0.691 as d-Stat values; and giving 1135.1, 658.4, 1132.9 and 2675.7 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 44).

That was due to *peronospora* infection which attacked the plants, in addition to, the thunder storm that attacked the field during the month before end of the growing cycle. These two problems caused losses in the broken and weak shoots and cuts in some leaves and fruits, although, plants recovered and continued till the end of their life cycle (Fig. 21). The model was able to simulate total dry matter accumulation at the other three transplanting dates with d-Stat values near to the optimal value of 1 and low RMSE values.

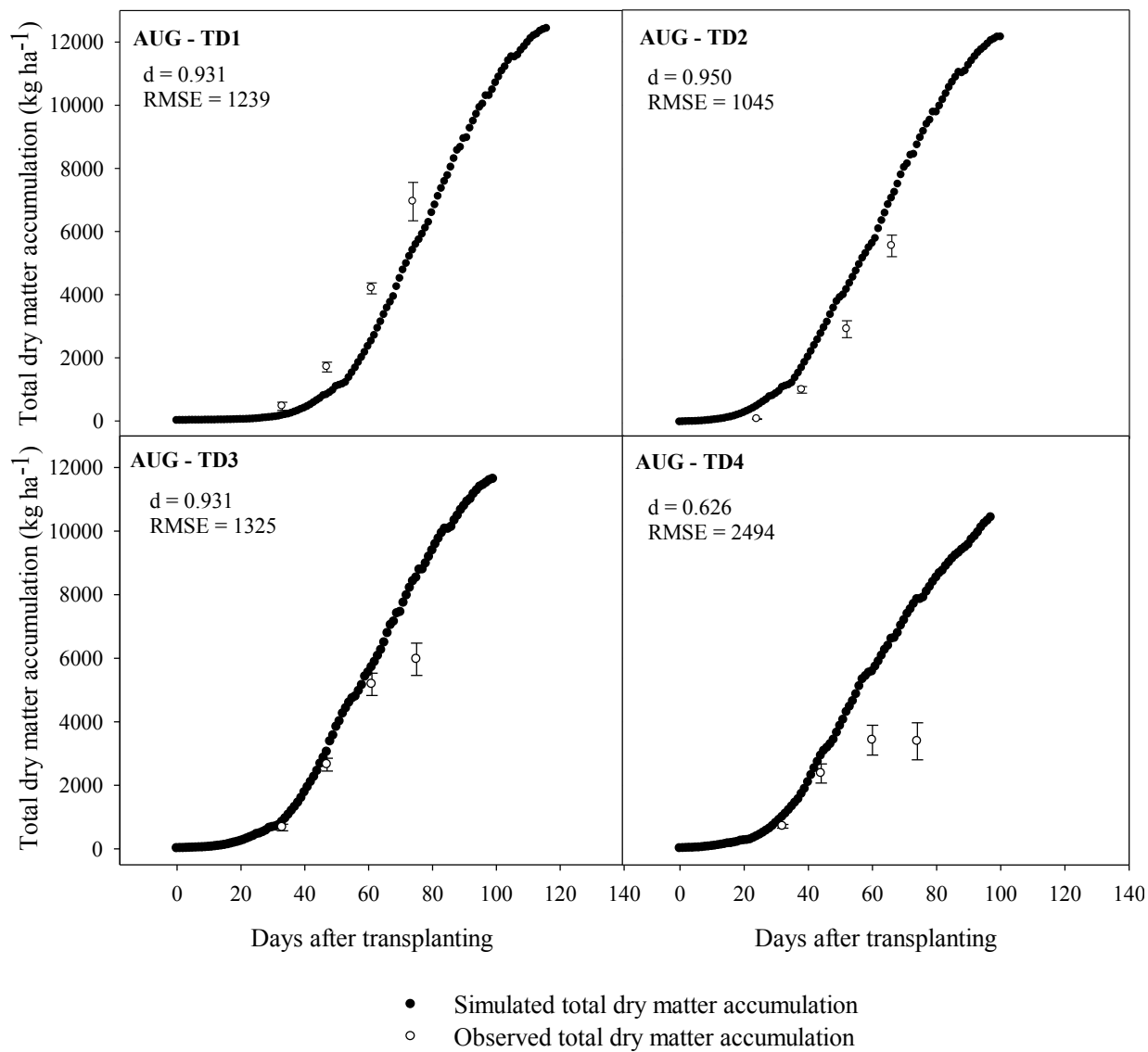


Figure 43: Simulated and observed total dry matter accumulation (TDM) for AUG processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

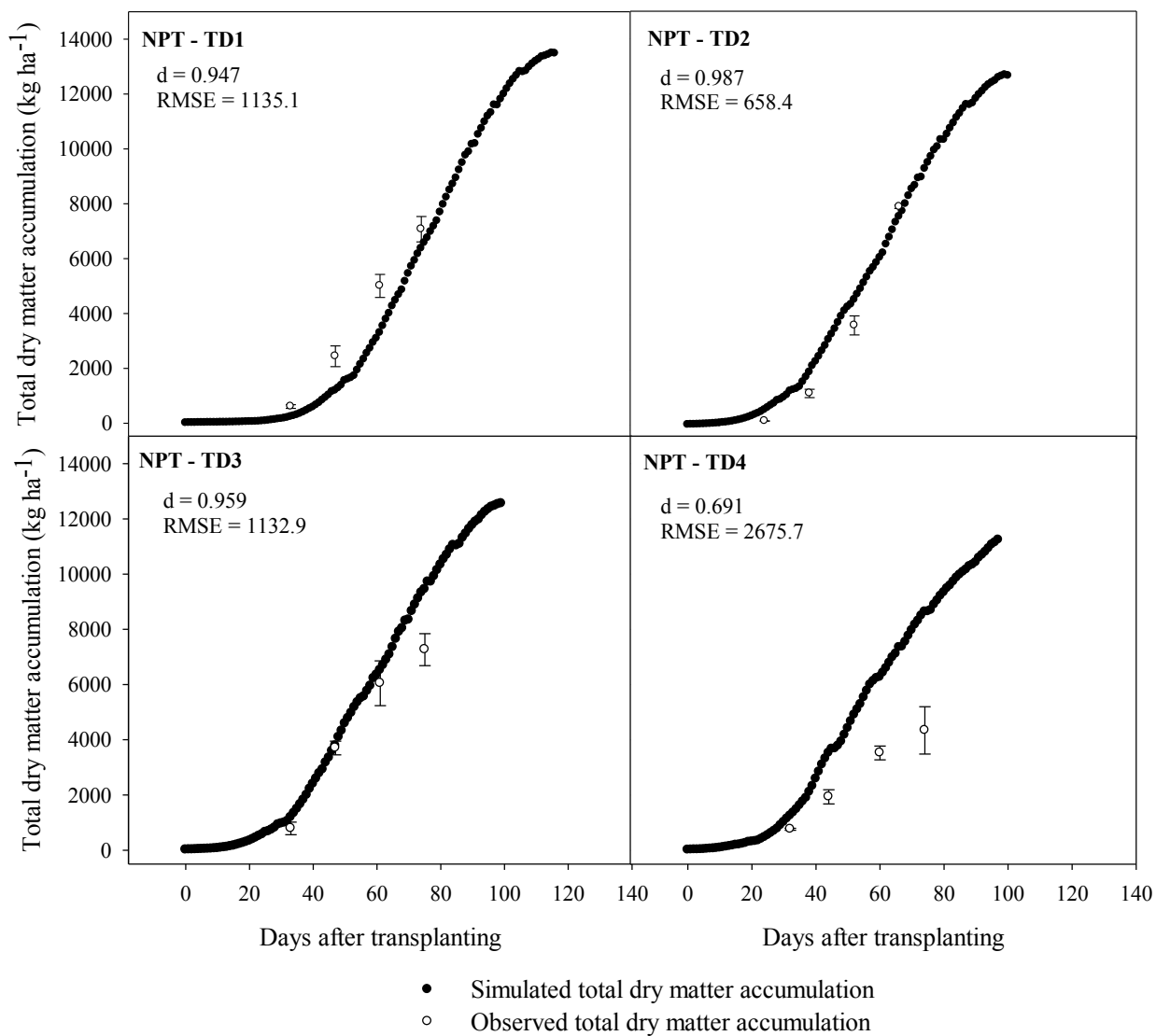


Figure 44: Simulated and observed total dry matter accumulation (TDM) for NPT processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

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### 3.3.2.2. Fruits dry matter accumulation

Comparing model performance at different transplanting dates for AUG variety showed that d-Stat values between observed and simulated fruits dry matter accumulation were 0.670, 0.997, 0.981, and 0.570 for TD1, 2, 3 and 4, respectively, while RMSE values were 1632, 121, 374, and 1608 kg ha<sup>-1</sup>, respectively (Figure 45). NPT variety had similar simulation to AUG variety giving 0.638, 0.968, 0.994 and 0.647 as d-Stat values; and giving 1814.3, 487.6, 249.7 and 1681.3 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 46).

Figure 22 indicate that the model performance at TD1 was taking the same tendency for both observed and simulated evolution but the model started the fruit formation late with about 10 days due to model reaction with low air temperature. The reason for model over prediction at TD4 near to end of the growing cycle could be due to *peronospora* infection and thunder storm that attacked the field during the last month of plants life cycle. That resulted in fruits partial injuries by broken shoots and fungal infection.

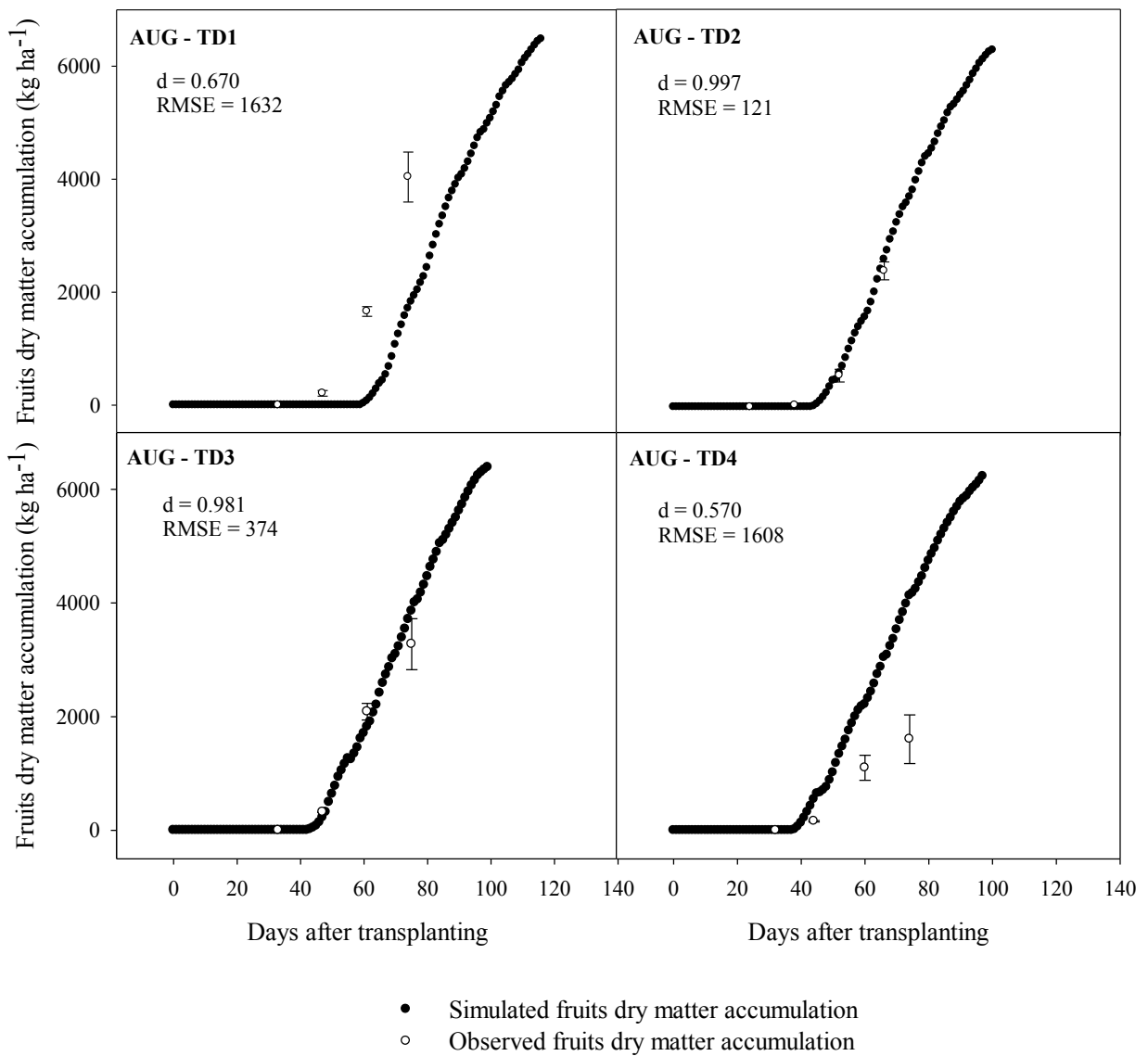


Figure 45: Simulated and observed fruits dry matter accumulation (FDM) for AUG processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

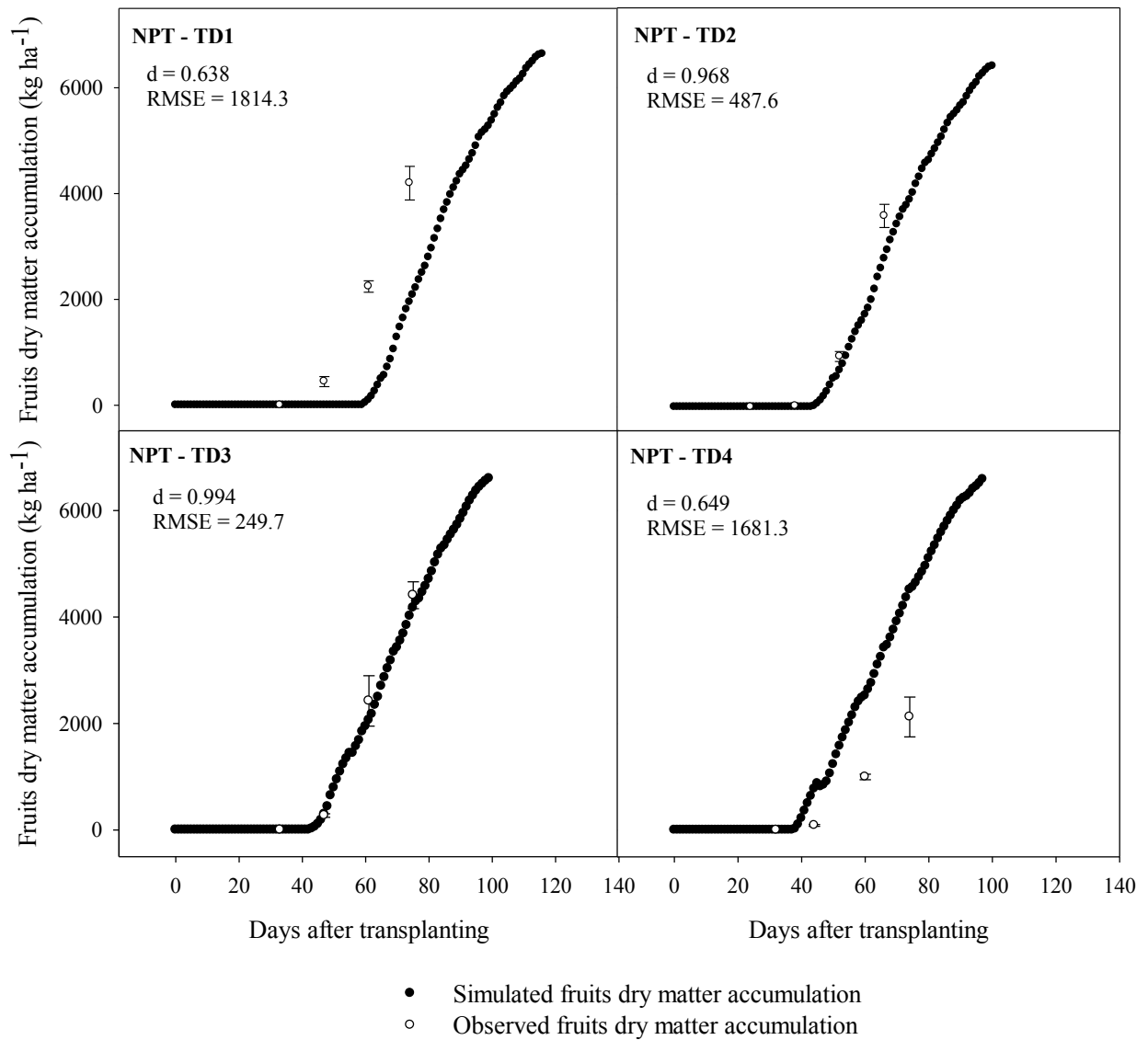


Figure 46: Simulated and observed fruits dry matter accumulation (FDM) for NPT processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

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### 3.3.2.3. Fruits fresh weight accumulation

Fruits fresh weight is a new evaluating parameter was added in the 4.5 version of DSSAT model to evaluate the actual fresh yield of tomato plants. This parameter is affected by weather conditions, agronomic practices, and variety genetic characteristics. Figure 47 shows that fruit yield was well simulated by the model for AUG variety under TD2 and 3; giving excellent values for d-Stat (0.997 and 0.978, respectively) and relatively low RMSE values (2194 and 7910 kg ha<sup>-1</sup>, respectively). Simulation accuracy for yield at TD1 (0.612 for d-Stat, and 38501 kg ha<sup>-1</sup> for RMSE) was low compared to other transplanting dates, as model prediction is less effective at low air temperature. Simulation at TD4 was over than observed one (0.570 of d-Stat and 32475 kg ha<sup>-1</sup> of RMSE) at the end of the growing cycle due to *peronospora* infection and thunder storm that attacked plants during last month of growing cycle. Processing tomato variety at the four different transplanting dates during the spring 2010 growing season. NPT variety had similar simulation to AUG variety giving 0.570, 0.981, 0.997 and 0.587 as d-Stat values; and giving 35711.9, 6200.3, 3415.8 and 36749.6 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 48).

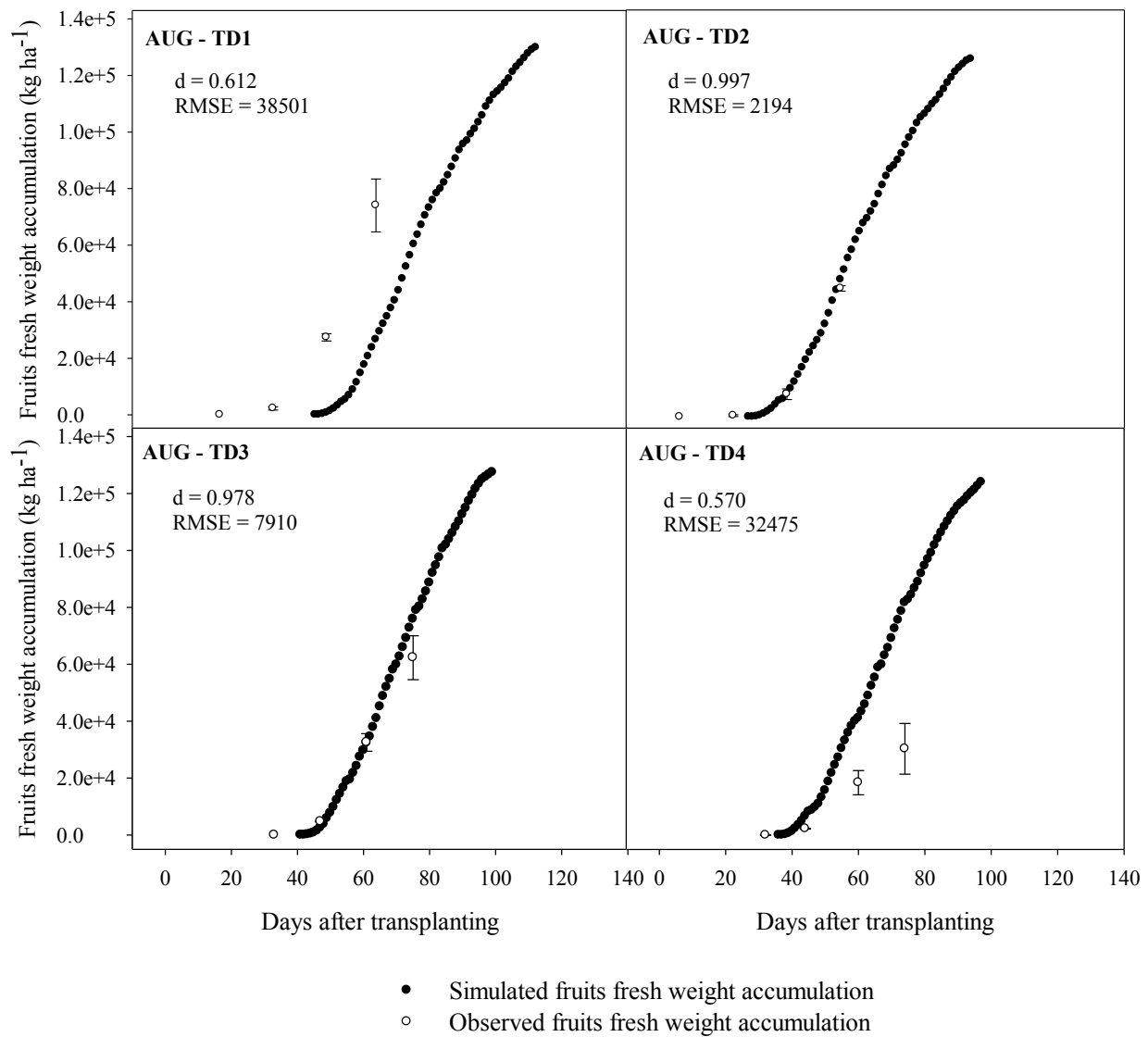


Figure 47: Simulated and observed fresh fruits weight accumulation (FFW) for AUG processing tomato variety at the four different transplanting dates during the spring 2010 growing season.



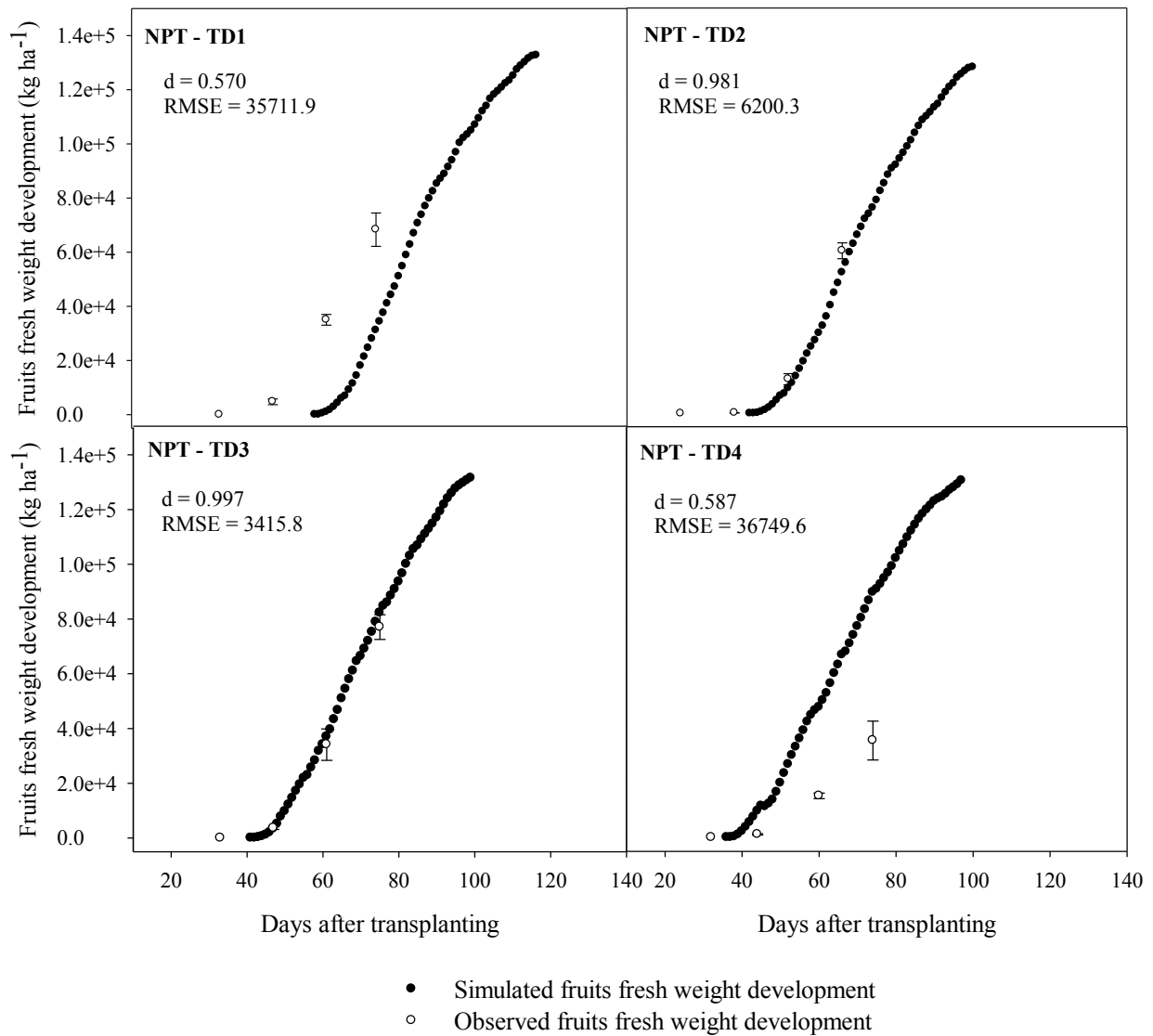


Figure 48: Simulated and observed fresh fruits weight accumulation (FFW) for NPT processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

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#### 3.3.2.4. Vegetative dry weight accumulation

Figure 49 shows model simulation of the observed vegetative dry matter accumulation for AUG variety at different transplanting dates. Calibration indices at the four transplanting dates showed good indications for d-Stat values (0.945, 0.887, 0.802 and 0.622, respectively) and low RMSE values (540, 967, 1098 and 1109 kg ha<sup>-1</sup>, respectively) with good simulation at the beginning of growing cycle then it was over simulation at the end of the growing cycle. NPT variety had similar simulation to AUG variety giving 0.865, 0.945, 0.769 and 0.647 as d-Stat values; and giving 918.2, 772.1, 1292.9 and 1239.1 kg ha<sup>-1</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 50).

Over simulation at TD4 was due to *peronospora* infection and thunder storm that attacked the field during last month of the growing cycle. That was resulted in losses in part of the vegetative biomass. Model was able to simulate vegetative growth evolution quite good when air temperature was more favorable for tomato plants.

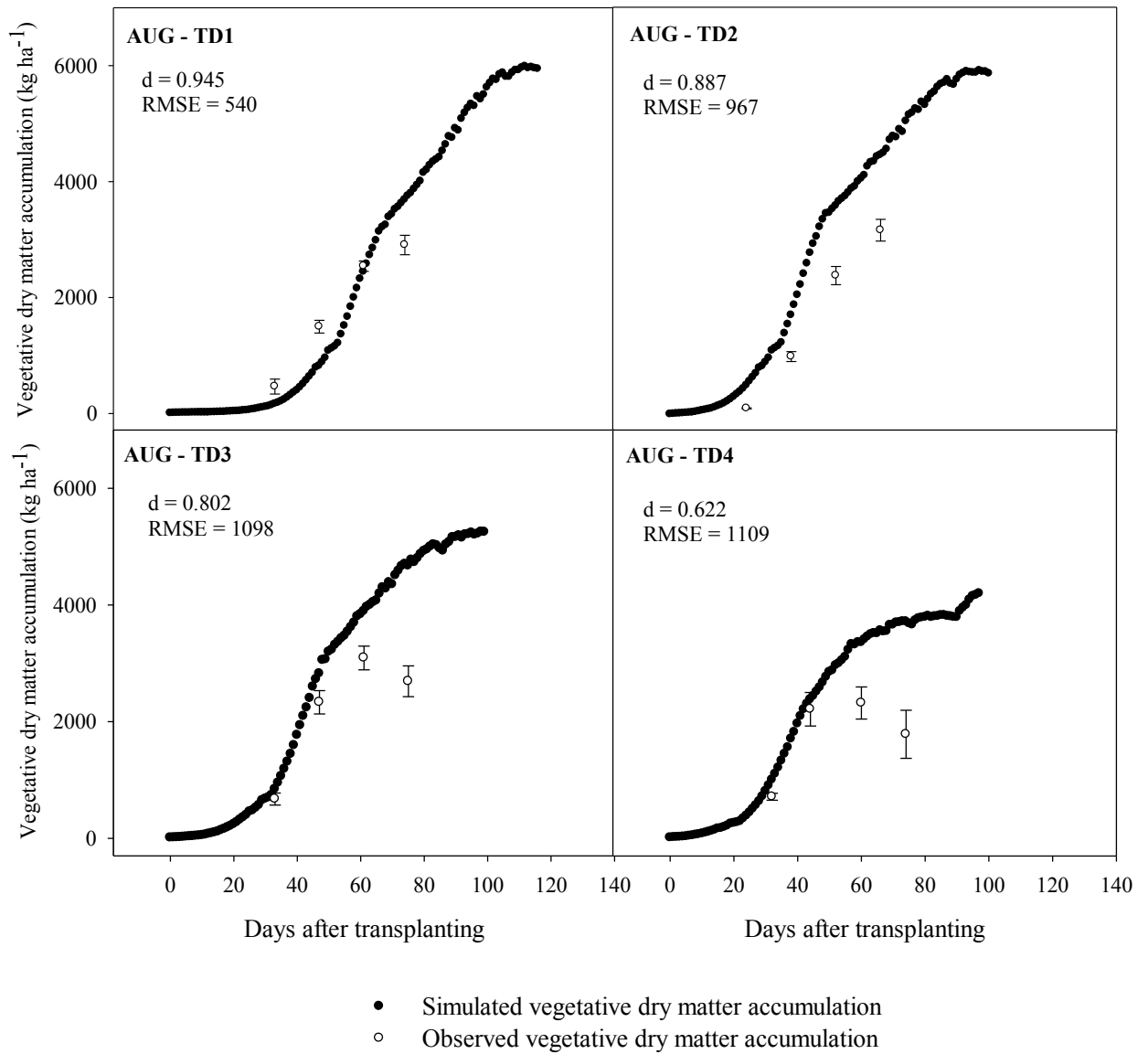


Figure 49: Simulated and observed vegetative dry matter accumulation (VDM) for AUG processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

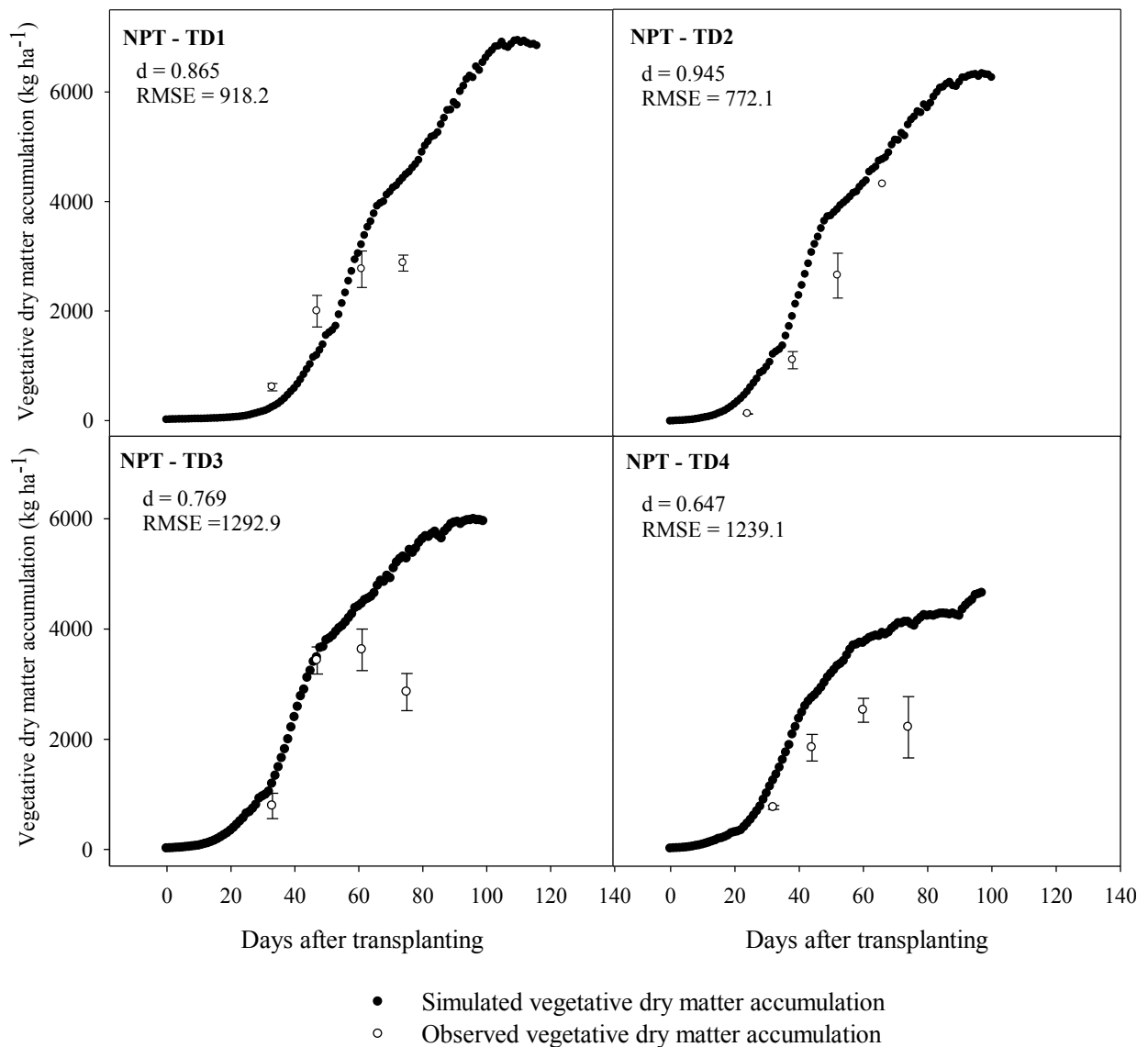


Figure 50: Simulated and observed vegetative dry matter accumulation (VDM) for NPT processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

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### 3.3.2.5. Number of fruits m<sup>-2</sup>

Evolution for number of fruits per m<sup>2</sup> was evaluated to see the match between its observed and simulated values (Figure 51). For AUG variety, model under TD2 and TD3 conditions gave relatively good simulation during the growing cycle (0.965 and 0.942 for d-Stat and 25 and 23 fruits m<sup>-2</sup> for RMSE). For TD1 the model gave under simulation (0.646 for d-Stat and 105 fruits m<sup>-2</sup> for RMSE), which was due to less model efficiency at low air temperature for early transplanting date. The simulation of plants at TD4 was over the observed value giving 0.548 of d-Stat value, and 77 fruits m<sup>-2</sup> of RMSE value. That was due to damages and losses of fruits during the last month of the growing cycle when there were *peronospora* infection and thunder storm attacked the field and caused that losses. NPT variety had similar simulation to AUG variety giving 0.599, 0.938, 0.821 and 0.633 as d-Stat values; and giving 126, 36, 49 and 46 fruits m<sup>-2</sup> as RMSE values for TD1, 2, 3 and 4, respectively (Figure 52).

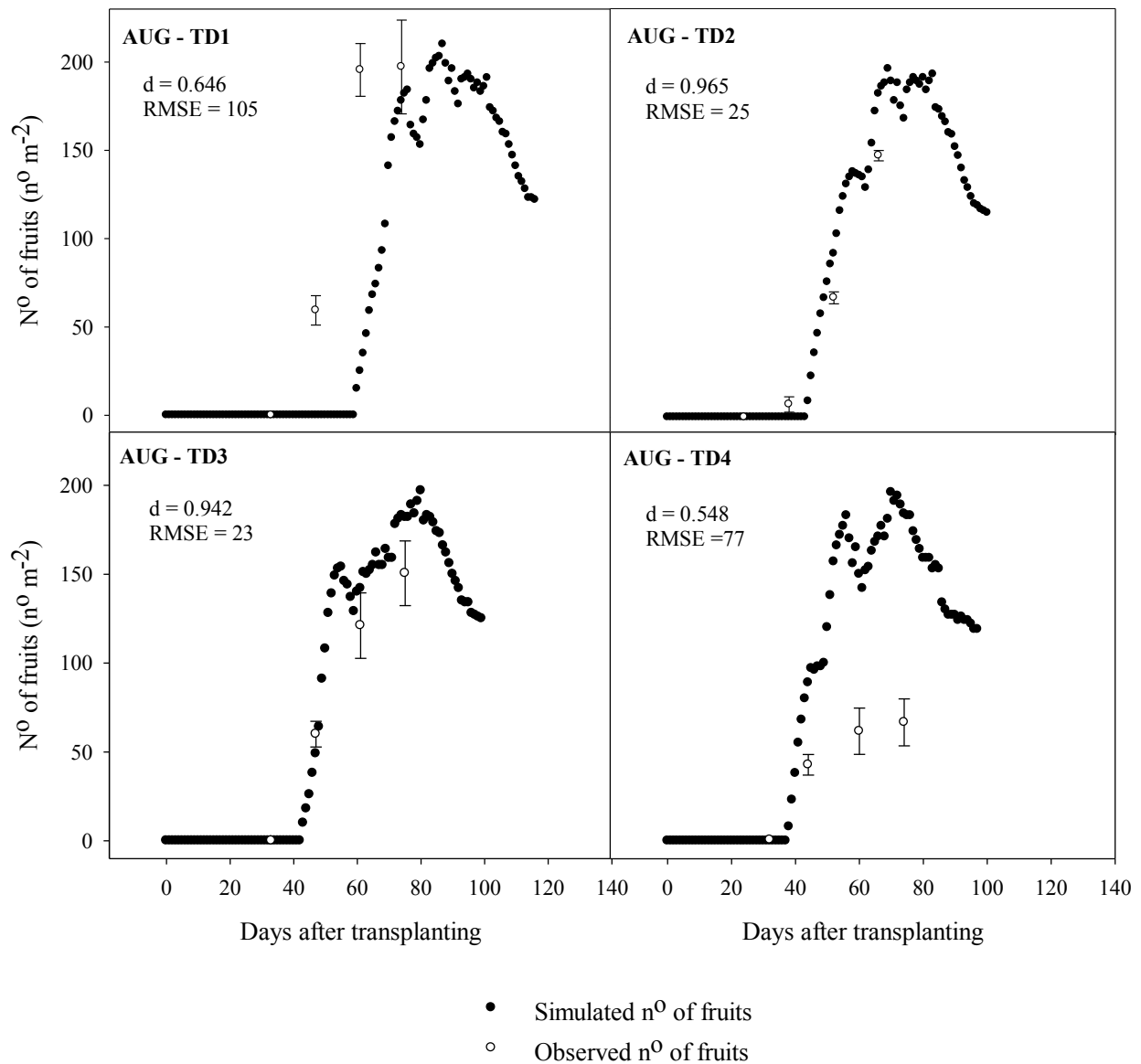


Figure 51: Simulated and observed number of fruits per  $\text{m}^2$  for AUG processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

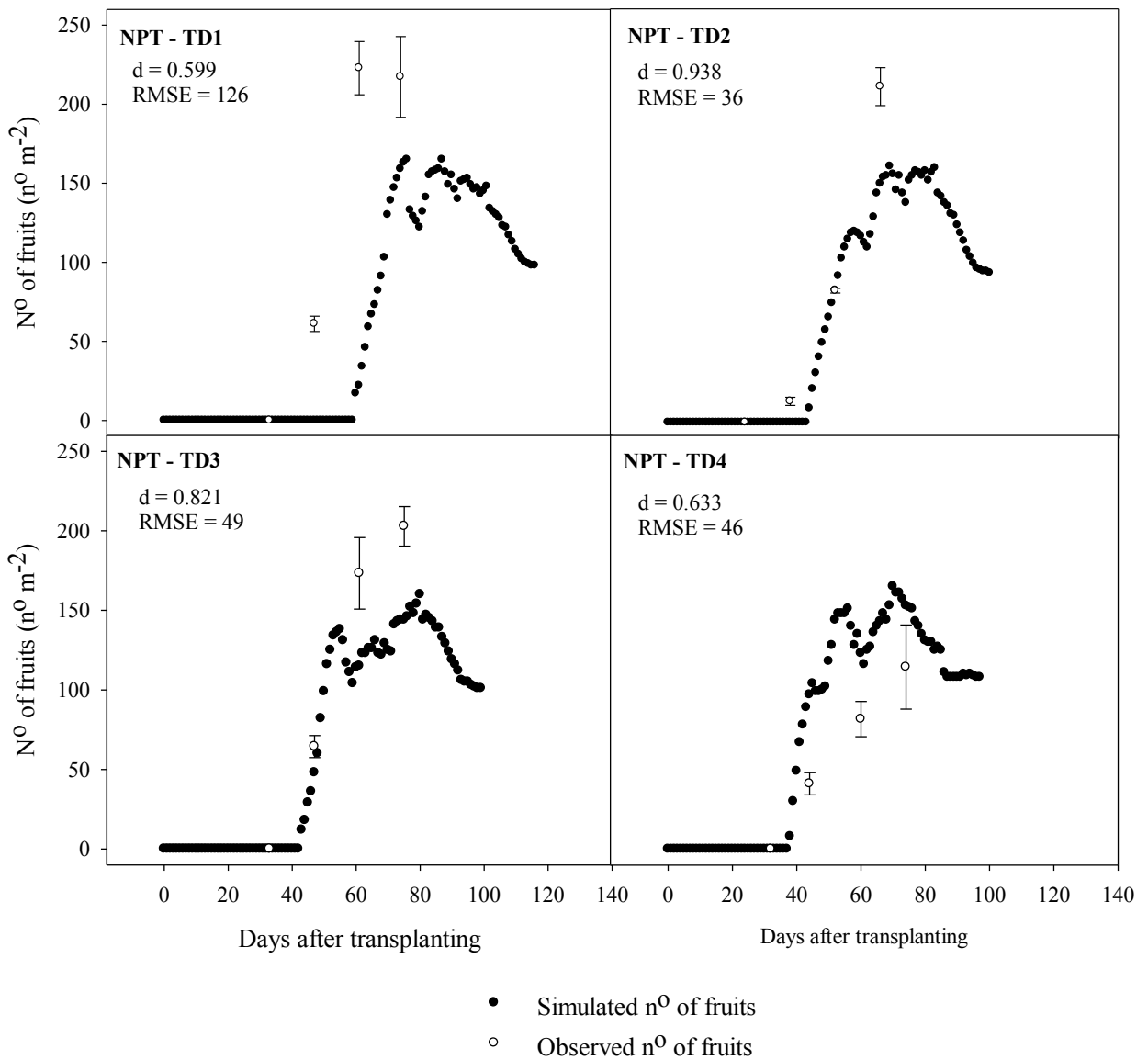


Figure 52: Simulated and observed number of fruits per  $\text{m}^2$  for NPT processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

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### 3.3.2.6. Harvest index

Evaluation of plants harvest index over time was done in order to see model performance for AUG variety at different transplanting dates (Figure 53). Comparing observed and simulated evolution showed that TD2, 3 and 4 were well fitted giving d-Stat values of 0.980, 0.948 and 0.920, respectively; Whereas RMSE for them was 0.05, 0.08 and 0.09, respectively. For TD1, the agreement between observed and simulated evolution for harvest index was lower giving 0.924 for d-Stat and 0.27 for RMSE indices. Low temperature at the early transplanting caused late prediction for the rise of harvest index. NPT variety had similar simulation to AUG variety giving 0.563, 0.938, 0.921 and 0.861 as d-Stat values; and giving 0.31, 0.09, 0.11 and 0.12 as RMSE values for TD1, 2, 3 and 4, respectively (Figure 54). In general, prediction of harvest index in calibration and validation phases were quite high compared to other evaluation parameters.



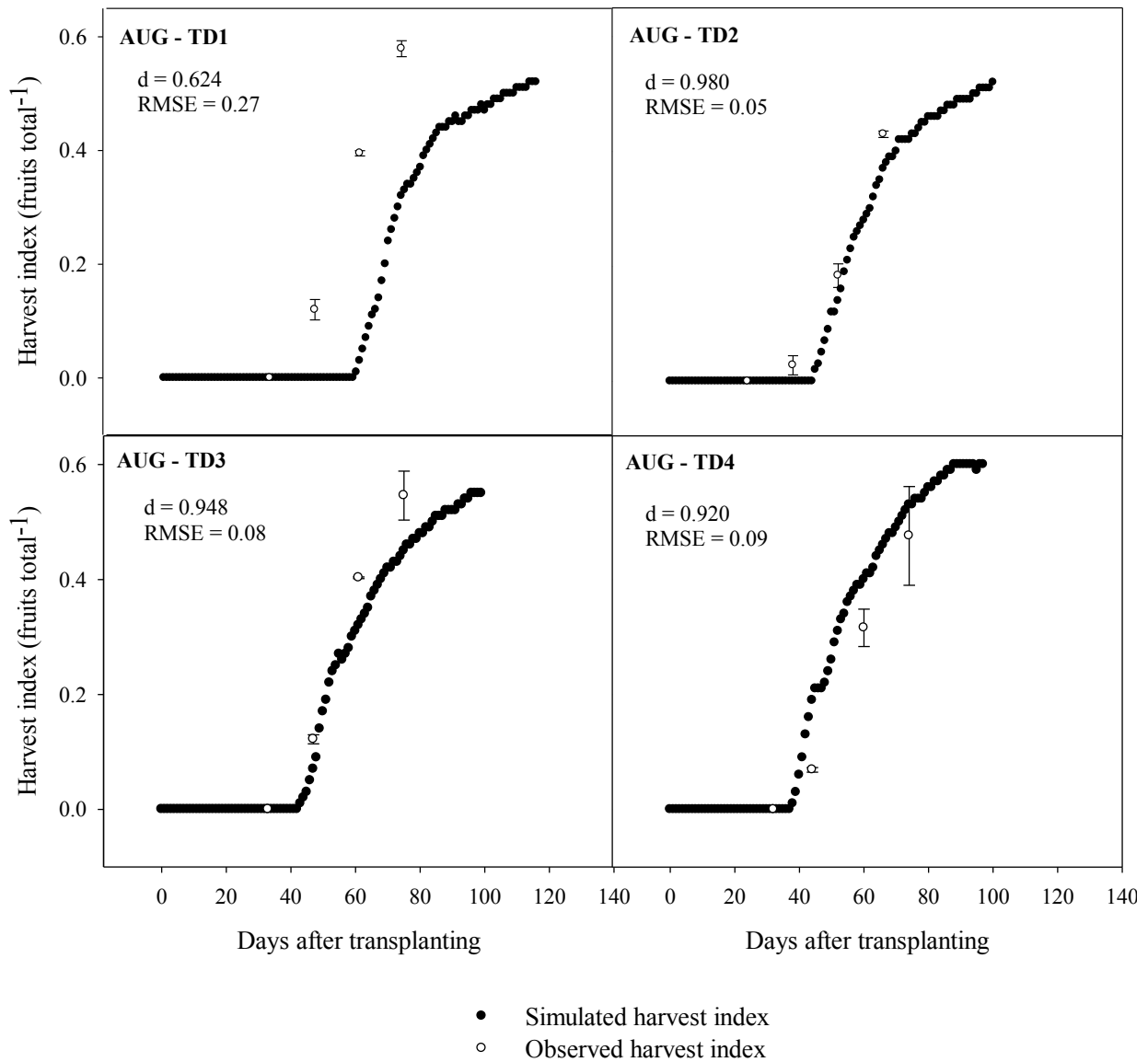


Figure 53: Simulated and observed harvest index (HI) for AUG processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

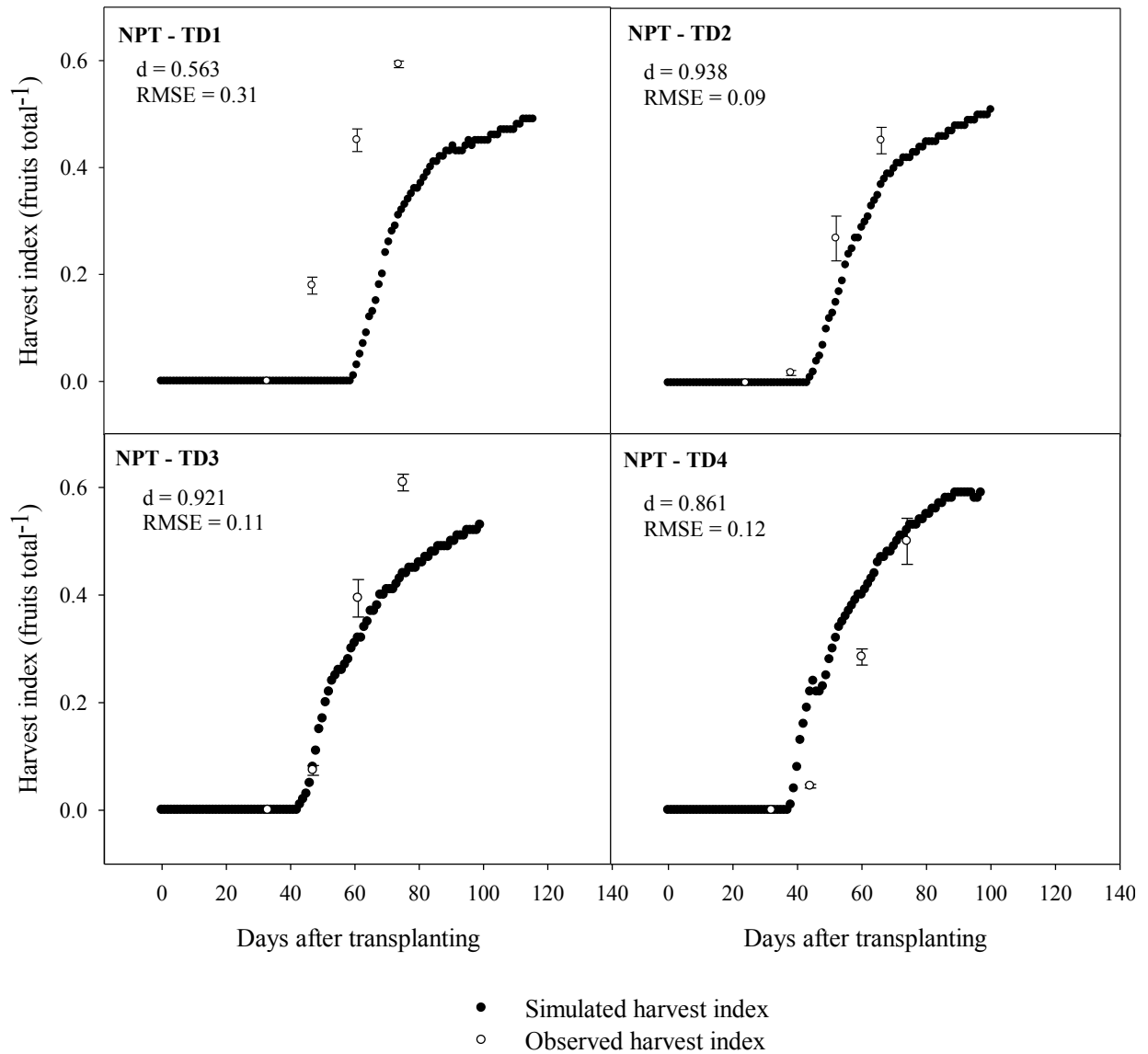


Figure 54: Simulated and observed harvest index (HI) for NPT processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

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### 3.3.2.7. Leaf area index

Simulation of leaf area index using CSM-CROPGRO-Tomato model was relatively low compared to the other growth parameters (Figures 55 &56). For AUG variety, it was well simulated under TD1 and TD2 conditions (0.784 and 0.728 of d-Stat, respectively; and 0.69 and 0.74 of RMSE, respectively), whereas it gave unsatisfied under simulation for TD3 and 4, giving d-Stat values of 0.661 and 0.542, respectively; and RMSE values of 0.65 and 0.52, respectively. NPT variety had similar simulation to AUG variety giving 0.862, 0.660, 0.634 and 0.738 as d-Stat values; and giving 0.49, 1.15, 0.75 and 0.23 as RMSE values for TD1, 2, 3 and 4, respectively.

Simulated LAI fitted the measured data during initial growth as shown by a slow increasing of LAI due to the transplant shock and the crop being source limited due to incomplete light interception. Thereafter, the fit was less perfect possibly due to large variability in the observed data. These results were in accordance with Scholberg *et al.* (1997), as well as Rinaldi *et al.* (2007) findings who found that simulated LAI increased slower than measured ones probably because the model does not take into account the twin rows plant distribution and overestimates the competition for light among plants.

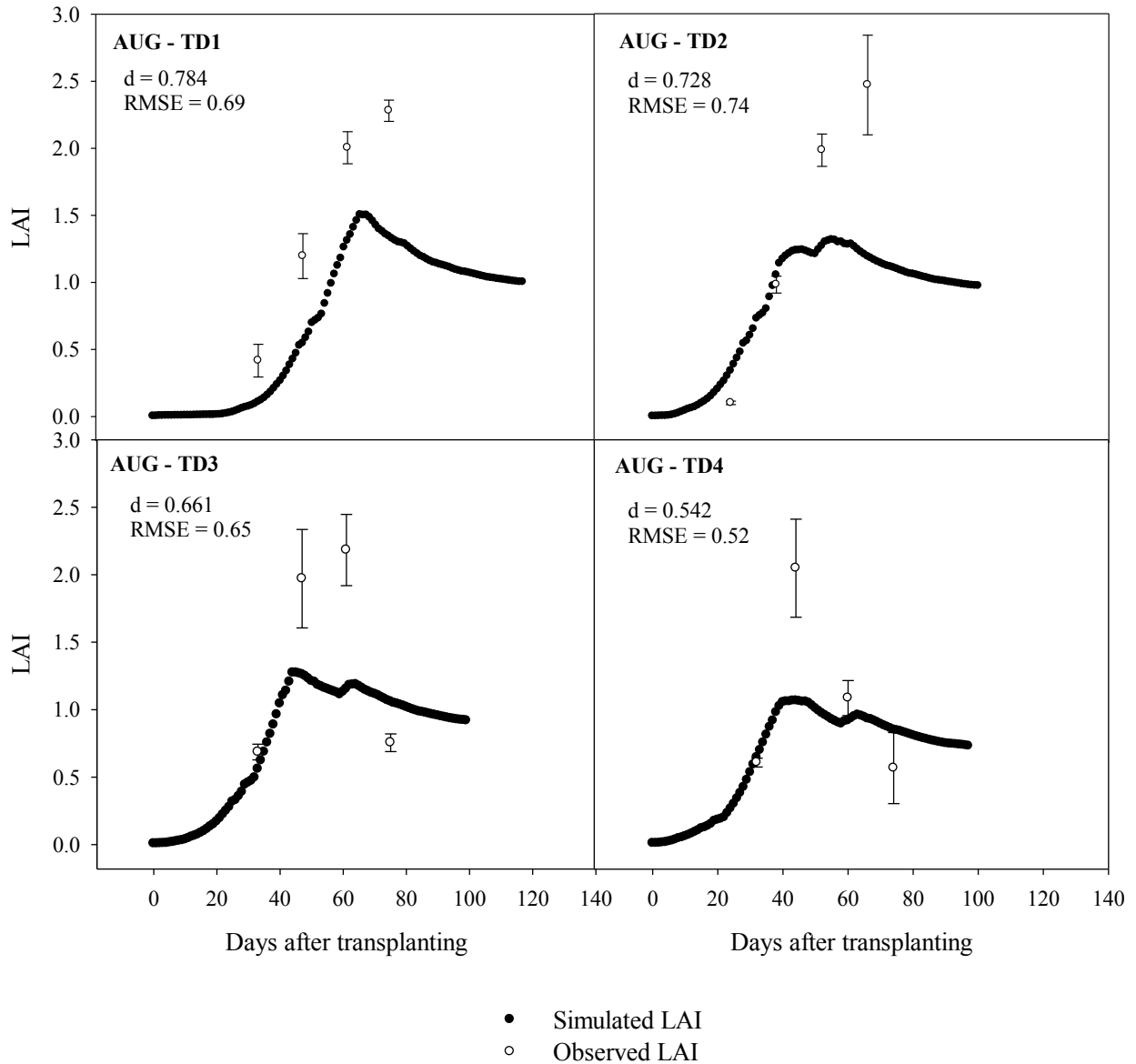


Figure 55: Simulated and observed leaf area index (LAI) for AUG processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

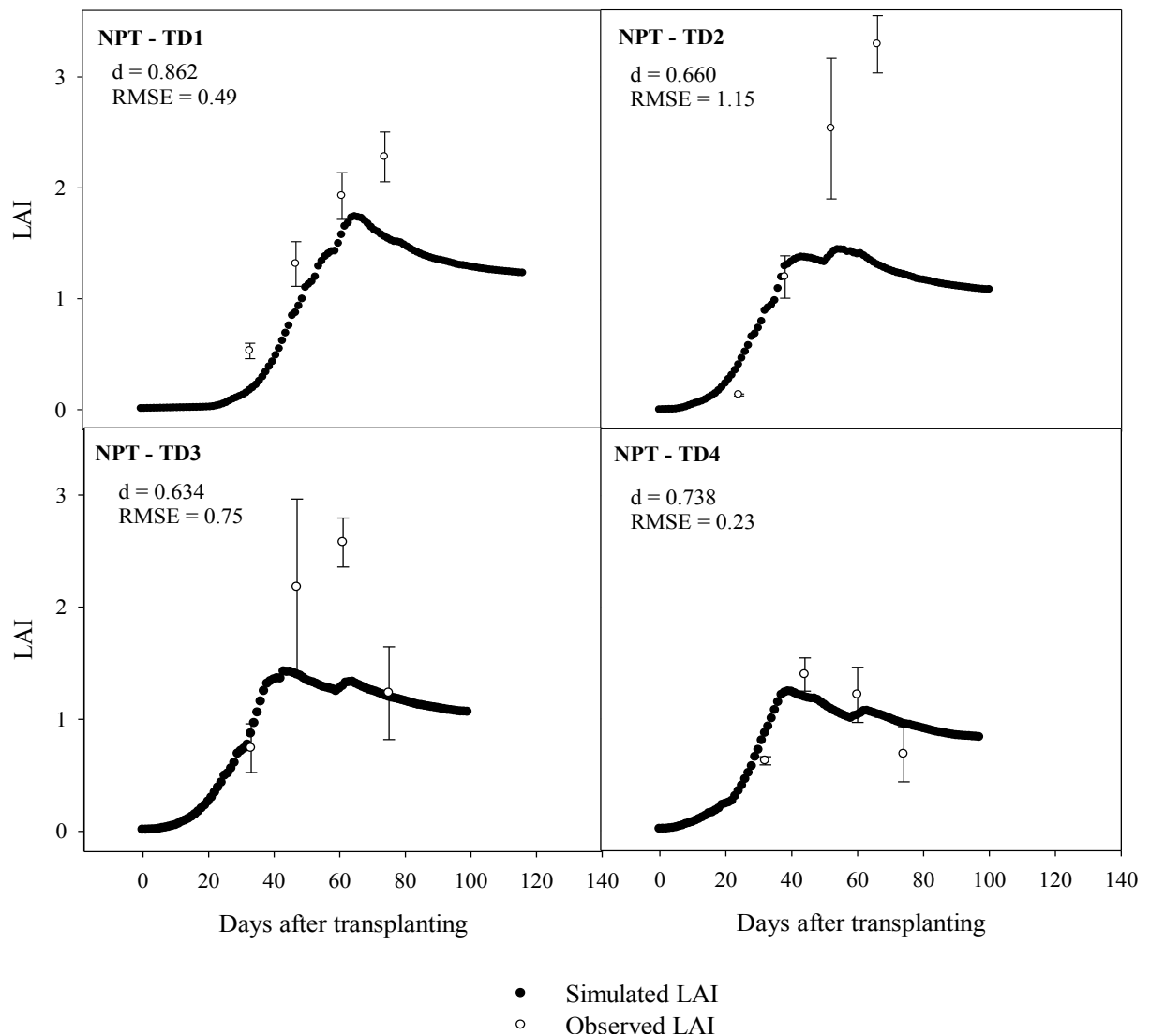


Figure 56: Simulated and observed leaf area index (LAI) for NPT processing tomato variety at the four different transplanting dates during the spring 2010 growing season.

### 3.3.2.8. Final remarks

Validation process confirmed that: efficiency of model simulation was high for total plant dry matter, fruits fresh and dry weight, and harvest index; medium for vegetative dry weight and number of fruits, and low for leaf area index of field-grown processing tomato for the four varieties under study. It also confirmed that first transplanting date had low simulation efficiency compared to other transplanting dates.

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### **3.4. Conclusion**

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The evaluation of the CSM-CROPGRO-Tomato model following calibration steps for field-grown processing tomato showed a good performance of simulated values when comparing it with observed data. The model simulated yield very well for the second, third, and fourth planting dates for all varieties in 2009. Validation activity confirmed that CSM-CROPGRO-Tomato model is able to simulate tomato maturity date, fruit number, tops and fruit yield at harvest. In particular, total plant dry matter, fruits fresh and dry weight, and harvest index were accurately predicted and simulation results are satisfactory for our objectives. Leaf area index was poorly simulated during both calibration and validation phases of model evaluation, which was due to limited model prediction for light competition of twin row cultivation. Variety of measurements among observed plants could be also a reason for such inaccuracy among observed and simulated evolution in leaf area index.

Transplanting at early date gave over simulation by the model in most cases. That was because of over prediction of model at lower temperature and longer growing cycle. Model could give better simulation by future changes in temperature when it will be warmer at the beginning of growing season. Plant growth was well simulated under weather conditions of the other three transplanting dates, giving growth efficiency for the second and third transplanting dates compared with the fourth transplanting dates. This evaluation can help farmers to better manage their cultivation, can help breeders to think about suitable variety characteristics for each location conditions, and can help decision makers to define the best period of processing tomato trade at national level.

Using the two years datasets of different weather conditions to calibrate and validate the model confirmed the use potential of this model to be utilised as a decision making tool for both farmers and decision makers at regional level. Weather conditions were different along growing seasons of years 2009 and 2010, giving semi-dry season in 2009 and humid season in 2010. These differences had more reliable effects on plant response, but the model was able to follow this response and it predicted it adequately in both seasons. This indicates that under

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northeastern Italian conditions it would be possible to use the model and to simulate the possible yield of different processing tomato varieties and different seasonal and weather conditions.

In order to evaluate the simulation capability of the model for a larger range of conditions, further work should be done regarding the genotype coefficients for each variety under study, especially for leaf area related parameters. CSM-CROPGRO-Tomato model is not yet designed for mulched conditions and further studies should be done in this regard as well. CSM-CROPGRO-Tomato simulation model could be used as a decision making tool helping in regional short term plans. Other tomato varieties could be taken into consideration in order to calibrate the model for other environmental and agronomic conditions. CSM-CROPGRO-Tomato is ready to be used under different future environmental scenarios in order to help in taking decision at long term national plans.

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## **Chapter 4**

# **Applying CSM-CROPGRO-Tomato Model to Study Climate Change Impacts and Adaptation Options for Field- grown Processing Tomato**



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## 4.1. Introduction

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Agriculture is sensitive to climate change in a variety of ways, not all negative. In mid- to high-latitude regions, particularly in the northern hemisphere, moderate increases in temperature and rainfall changes are expected to lead to a small gain in crop yields and livestock production (Easterling *et al.*, 2007). Increasing concentrations of CO<sub>2</sub> in the atmosphere may also benefit crop yields, making crops grow faster and more efficiently, although the extent to which this is the case is still debated (Environmental Protection Agency, 2010). Common weeds, for example, are found to benefit most from the CO<sub>2</sub> effect, which is one key factor counteracting its potential benefits (Backlund *et al.*, 2008).

Essentiality of meteorology application to agriculture was evaluated by WMO (2010) as most of agricultural practices rely on weather conditions. The objectives of this application are to emphasize these effects and to assist farmers in preparing themselves by applying this supportive knowledge and information in agrometeorological practices and through agrometeorological services. FAO (2007) stated that “Increased intensity and frequency of storms, drought and flooding, altered hydrological cycles and precipitation variance have implications for future food availability. The potential impacts on rainfed agriculture as well as irrigated systems are still not well understood”.

The DSSAT models, in our case CSM-CROPGRO-Tomato, have minimum requirements to run and evaluate their outputs and their simulation ability. One of these main requirements is the weather datasets, especially if we are studying the productivity and its relation with environmental impacts on a long term. The variability of weather parameters and extreme events could have a great impact on plant growth and fruit resistance till the end of the growing cycle or till harvest and maturity phases.

The Intergovernmental Panel on Climate Change (IPCC) developed long-term emission scenarios (Special Report on Emissions Scenarios, SRES) in 1990 and 1992. These scenarios have been widely used in the analysis of possible climate change, its impacts, and options to mitigate and adapt to climate change. In 1995, the IPCC 1992 scenarios were evaluated. The

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evaluation recommended that significant changes (since 1992) in the understanding of driving forces of emissions and methodologies should be addressed. The IPCC-AR4-SRES scenarios cover a wider range of energy structures than the IS92 scenarios, and they cover virtually all the possible directions of change, from high shares of fossil fuels, oil and gas or coal, to high shares of non-fossils. SRES scenarios extend the IS92 range toward higher emissions (SRES maximum of 2538 GtC compared to 2140 GtC for IS92), but not toward lower emissions. The SRES scenarios cover most of the range of carbon dioxide (CO<sub>2</sub>), other GHGs, and sulfur emissions found in the recent literature and SRES scenario database (Gualdi *et al.*, 2011).

IPCC four different storylines were developed to describe consistently the relationships between emission driving forces and their evolution and add context for the scenario quantification. The main driving forces of future greenhouse gas trajectories will continue to be demographic change, social and economic development, and the rate and direction of technological change and this finding is consistent with the IPCC 1990, 1992 and 1995 scenario reports (IPCC, 2000).

In IPCC special report about emission scenarios (2000), the A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

Within the CIRCE project there are 5 regional ocean models dedicated to the Mediterranean Sea. Four of them are used as components of the Mediterranean regional climate system. MITgcm at 1/8° and 42 levels (Sannino *et al.* 2009, Artale *et al.* 2009) used at ENEA, and MPIOM (A.Elizalde, pers. comm.) at 1/8° and 29 z-levels used at MPI. In these scenarios, during the 21st Century period, the GHGs and anthropogenic aerosol have been specified according to the A1B IPCC-SRES (Nakicenovic *et al.* 2000). In the IPCC-AR4, the

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SRES-A1B scenario was given more emphasis, not because it was the most probable, but because it was the median scenario. These projections allow assessing the response of the Mediterranean Sea to climate change over the 1950-2050 period and under the A1B hypothesis as well as a large part of the associated uncertainty.

Model used to apply these future scenarios on processing tomato was a beta version of CSM-CROPGRO-Tomato model (Hoogenboom *et al.*, 2009). This model has functions to explore different experimental conditions, as well as different climatic conditions. It has also functions that allow users to ask ‘what if?’ questions, so it gives a wide range of choices to be used as simulation options. Number of years to be simulated and simulation starting date can also specified for each chosen experimental season. Options of simulation can be used are for water, nitrogen, potassium, phosphorus, symbiosis, chemicals, diseases, tillage and CO<sub>2</sub> levels. Methods used to measure weather parameters, photosynthesis, initial soil conditions, hydrology, evapotranspiration, soil organic matter, infiltration, soil evaporation and soil layer distribution can be also determined through model interface. Management of planting, irrigation, nitrogen, organic amendments and harvesting are as well part of simulation choices. Series of model outputs can be determined though adjusting some options including frequency of outputs, overview, summary, as well as some details related to management outputs. In our study, we used some of these options related to management, planting and years of simulation, in order to obtain an overview about processing tomato growth transplanted in the open field at different transplanting dates and their response at different climate conditions.

The objective of this chapter is to estimate future field-grown processing tomato plant growth and yield by applying CSM-CROPGRO-Tomato model using two different future weather scenarios, which are ENEA (scenario 1) and MPI (scenario 2) for the coming 40 years. The work aimed also to recommend some adaptation options for both farmers and breeders in order to have better tomato growth and yield in the near future.

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## 4.2. Materials and Methods

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### 4.2.1. Weather historical and future data series

After evaluating the CSM-CROPGRO-Tomato model using two observed datasets of years 2009 and 2010, historical 20 years of daily observed weather data series were collected and rearranged according to weather file model format (FileW) of weatherman program. Future 40 years of daily weather data (from 2011 to 2050) were obtained using two different climate scenarios (Italian National Agency for New Technologies, Energy and Sustainable Eco, ENEA, Rome, Italy; and Max-Planck Institute for Meteorology, MPI, Hamburg, Germany). These data included the four main parameters (Figure 57) required to run the CSM-CROPGRO-Tomato model which are: solar radiation ( $\text{MJ}\cdot\text{m}^{-2}$ ), maximum temperature ( $^{\circ}\text{C}$ ), minimum temperature ( $^{\circ}\text{C}$ ), and precipitation (mm).

Comparing the available real historical data (from 1964 to 2010) and the two scenarios, we can see that the two scenarios gave better estimations for maximum temperature, minimum temperature, and total precipitation were better than total solar radiation (Figure 57). Future estimations (from 2011 to 2050) of both scenarios showed that rise in mean temperature was around  $2.8^{\circ}\text{C}$ , while total precipitation amount in scenario 1 was higher than in scenario 2 with about  $400\text{ mm year}^{-1}$ . Estimations of solar radiation was nearer to reality in scenario 1 (from  $5500$  to  $6000\text{ MJ m}^{-2}\text{ year}^{-1}$ ) more than in scenario 2 (from  $3500$  to  $4000\text{ MJ m}^{-2}\text{ year}^{-1}$ ).

Comparing the ratio between weather observed data for the period from 1964 to 2010 with the data series obtained from the two climate models for the same period, we can see some differences among them (Figure 58). For global solar radiation, we can see that the ratio between first scenario and observations was higher with range from 1.0 to 1.3, whereas it was lower with range from 0.7 to 0.9 for the ratio between second scenario and observations. For maximum temperature, the ratio for scenario 1 was higher with range from 0.9 to 1.1, and the ratio for scenario 2 was lower with range from 0.7 to 1.0. For minimum temperature, the ratio for scenario 1 was higher with range from 0.0038 to 0.0049, and the ratio for scenario 2 was lower with range from 0.0035 to 0.0043. For precipitation, the ratio for both scenarios was high at the first 5 years of the comparative period, while it varied in the period from 1995 to

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2002 to be 40 for scenario 1 and 80 for scenario 2, and for the period from 2003 to 2010 they were near to each other again with ratios ranged from 10 to 40. Estimation of the two scenarios for the maximum and minimum temperature and precipitation was near to reality more than their estimation for global solar radiation.

Such comparison of the two scenarios was done to have clearer idea about their possible influences on plants in the open field taking into consideration their deviation from reality. Plants can be affected by combination of different weather conditions. Evapotranspiration is defined by the interaction between air temperature and water losses from both soil (evaporation) and plants (transpiration), and it has a fundamental influence on plant growth and yield (Nagler *et al.*, 2005; Saseendran *et al.*, 2010).

#### **4.2.2. Open field experiment details**

Experimental location of this study was in Agripolis, L. Toniolo (45° 21' N; 11° 58' E), Italy. Two processing tomato varieties used in calibration and validation phases of CSM-CROPGRO-Tomato model have been used also in this study. The varieties were F1 (AUG) obtained from De Ruitter company; and NPT 63 (NPT) obtained from S&G company. The open field seedlings transplanting dates inserted in FileX of the model were four started at 21st April with 10 days interval with 10 days interval between the four transplanting dates (TD1, 2, 3, and 4). Irrigation and fertilization were set to be automatic in order to see the performance of the model after calibration. For more details about model data requirements, they can be found in chapter 3.

#### **4.2.3. Datasets used to evaluate the model**

In this study, the CSM- CROPGRO-Tomato model was evaluated using the non-mulched experimental datasets, which was the environmental condition used for initial model development. Experimental data were adjusted and some of them were calculated in order to fit model format. The experimental management details were entered into experimental detail file (FileX) using DSSAT V4.5 standardised format (Hoogenboom *et al.*, 2009). Soil profile

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descriptions for the experimental location were added to SOIL.SOL file of the DSSAT shell. Daily weather data set collected for the location was placed in the weather data files (FileW) for all the 20 years of historical weather (from 1991 to 2010), and the two future weather scenarios (from 2011 to 2050).

#### **4.2.4. Model simulation options used for future scenarios**

In order to simulate processing tomato growth across future years, simulation period were set at 40 years considering that simulation starts before dates of transplanting in order to consider initial conditions before the growing seasons. CO<sub>2</sub> level was set to ‘actual CO<sub>2</sub> Mauna Loa, Hawaii (keeling curve)’ option. Irrigation management at simulation options was set to ‘automatic when required’ option, in order to evaluate growth at the optimum water conditions and to avoid giving irrigation at rainy days at different scenarios conditions in the future weather data.

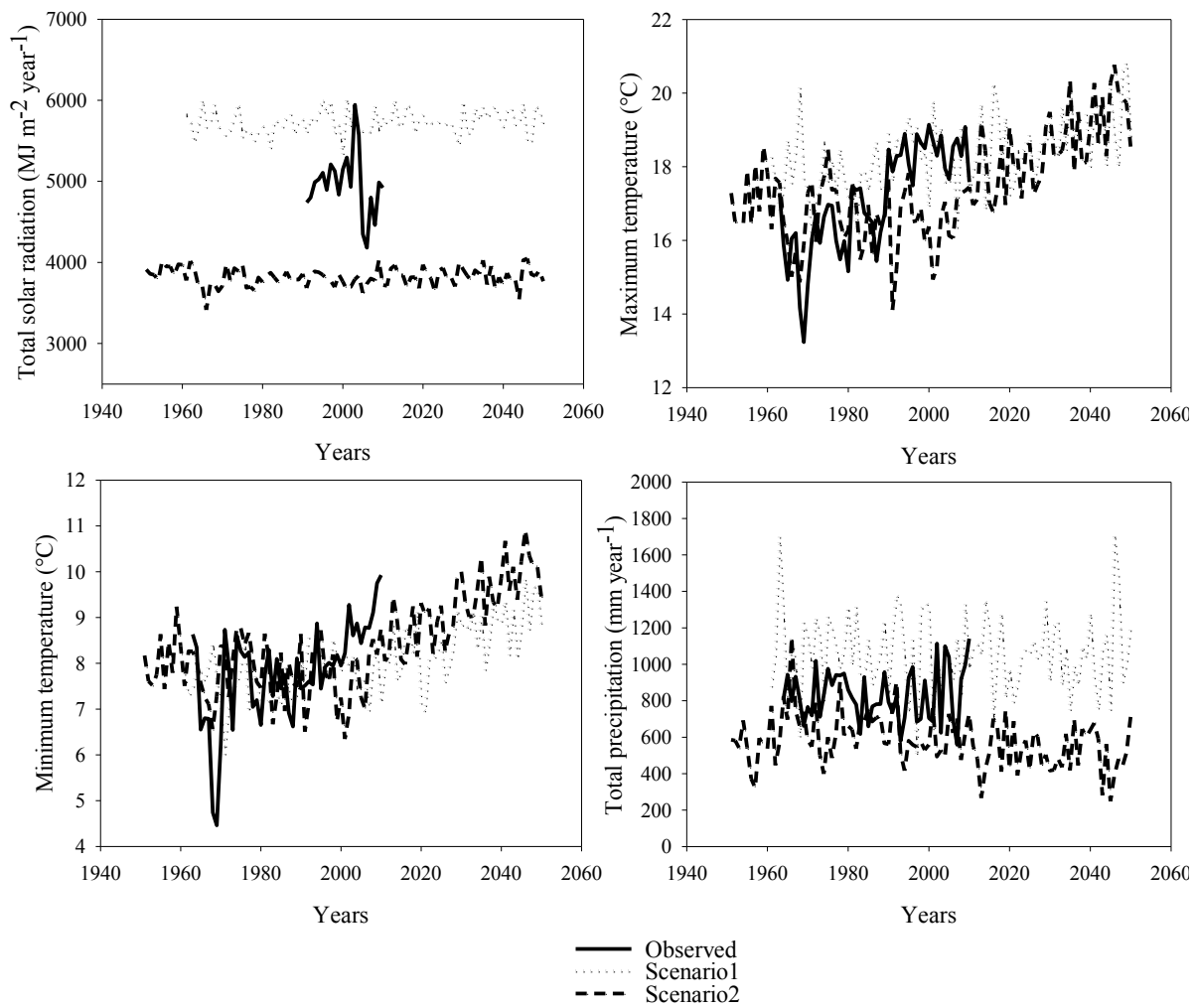


Figure 57: Historical and future annual weather data of total solar radiation, average maximum and minimum temperature, and precipitation for the period from 1951 to 2010 of historical data, and from 2011 to 2050 of future scenarios (ENEA: scenario1, and MPI: scenario2).



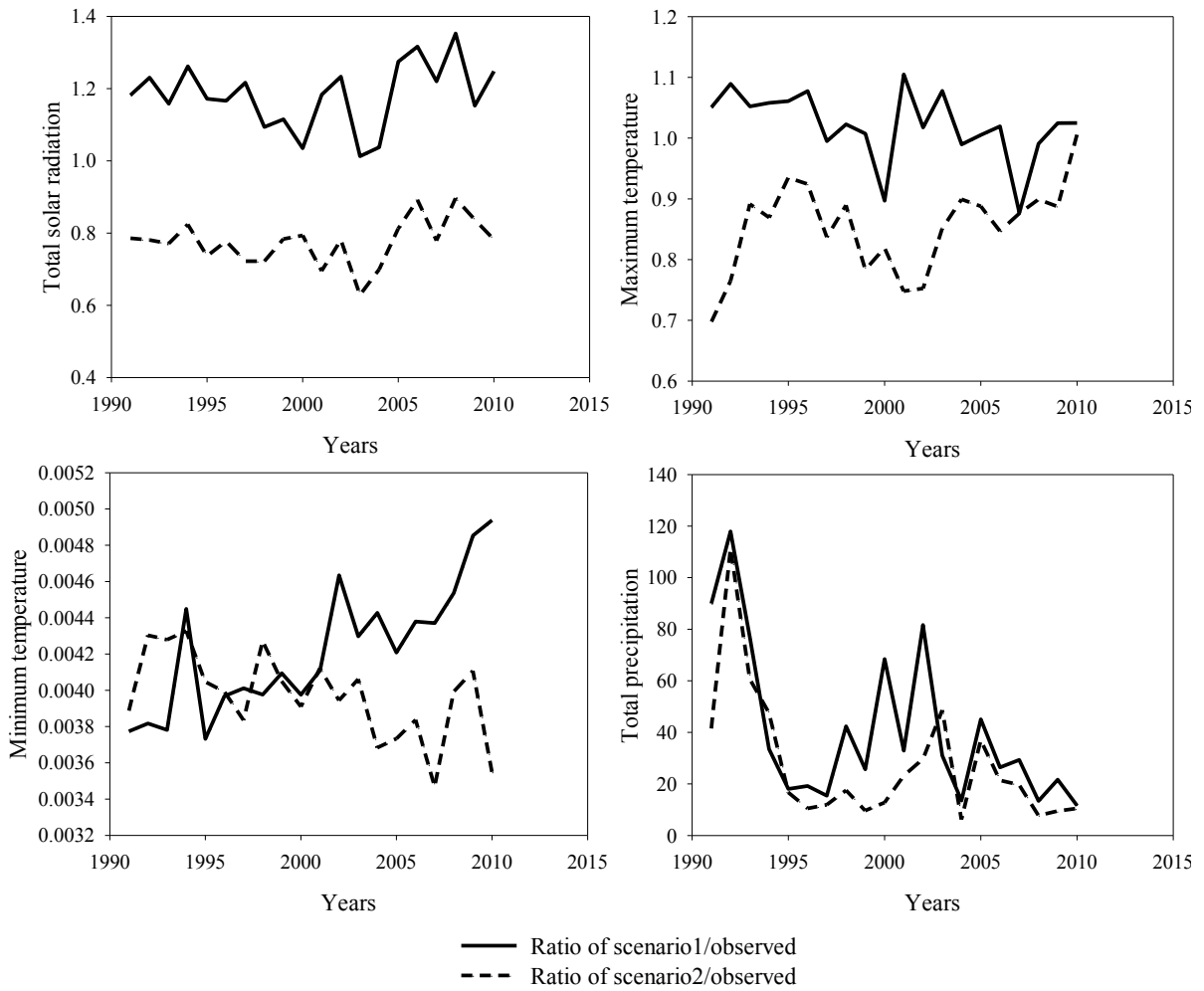


Figure 58: Annual ratio of weather data for the period from 1991 to 2010 between scenario 1 (ENE) and observed data, and scenario 2 (MPI) and observed data of total solar radiation, average maximum and minimum temperature, and precipitation.

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## 4.3. Results and Discussion

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### 4.3.1. Solar radiation variability in future years during tomato growing cycle

To characterize the total solar radiation for the ENEA scenario during the future period (Figure 59) we can see that moving from year 2011 to 2050 there will be a slight reduction near to stability among years. Reduction at the first three transplanting dates is almost the same giving higher total solar radiation at TD4 with about  $400 \text{ MJ m}^{-2}$  than other transplanting dates. If we consider different transplanting dates, we can see that at TD1, 2 and 3, the total solar radiation will range from  $4039.5 \text{ MJ m}^{-2}$  in 2011 to  $3957.1 \text{ MJ m}^{-2}$  in 2050, while at TD4 it will arrive to  $4207.3 \text{ MJ m}^{-2}$  in 2011 and to  $4119.9 \text{ MJ m}^{-2}$  in 2050.

For MPI scenario, reduction in total solar radiation during growing season from 2011 to 2050 is sharper than the ENEA scenario (Figure 60). At TD1, 2 and 3, total solar radiation ranges from  $2786.1 \text{ MJ m}^{-2}$  in 2011 to  $2561.9 \text{ MJ m}^{-2}$  in 2050, whereas it arrives from  $2862.7 \text{ MJ m}^{-2}$  in 2011 to  $2757.0 \text{ MJ m}^{-2}$  in 2050 at TD4. The total solar radiation values among years for growing cycle starts at all transplanting dates will range from 2300 to  $2900 \text{ MJ m}^{-2}$ .

According to outputs in figures 59 and 60, total solar radiation of the season along future years will vary from 4100 in 2011 to 3900 in 2050 for ENEA scenario, and from 2800 in 2011 to 2550 in 2050. Comparing values of figure 59 with values of figure 60, we can see that ENEA scenario supposes that total solar radiation during tomato growing season will be higher than MPI scenario with about  $1000 \text{ MJ m}^{-2}$ .

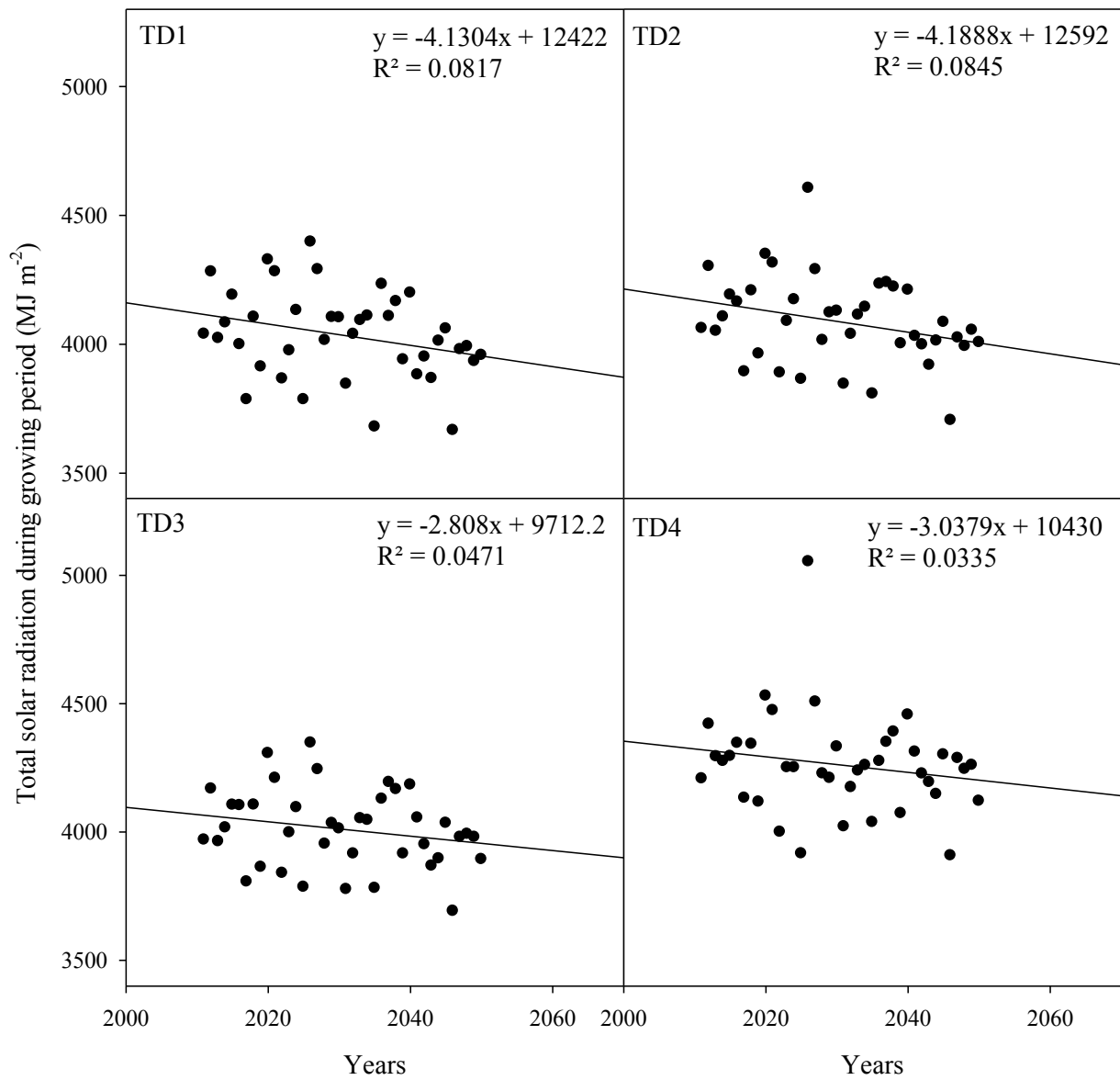


Figure 59: Changes in total solar radiation during growing period starting at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.

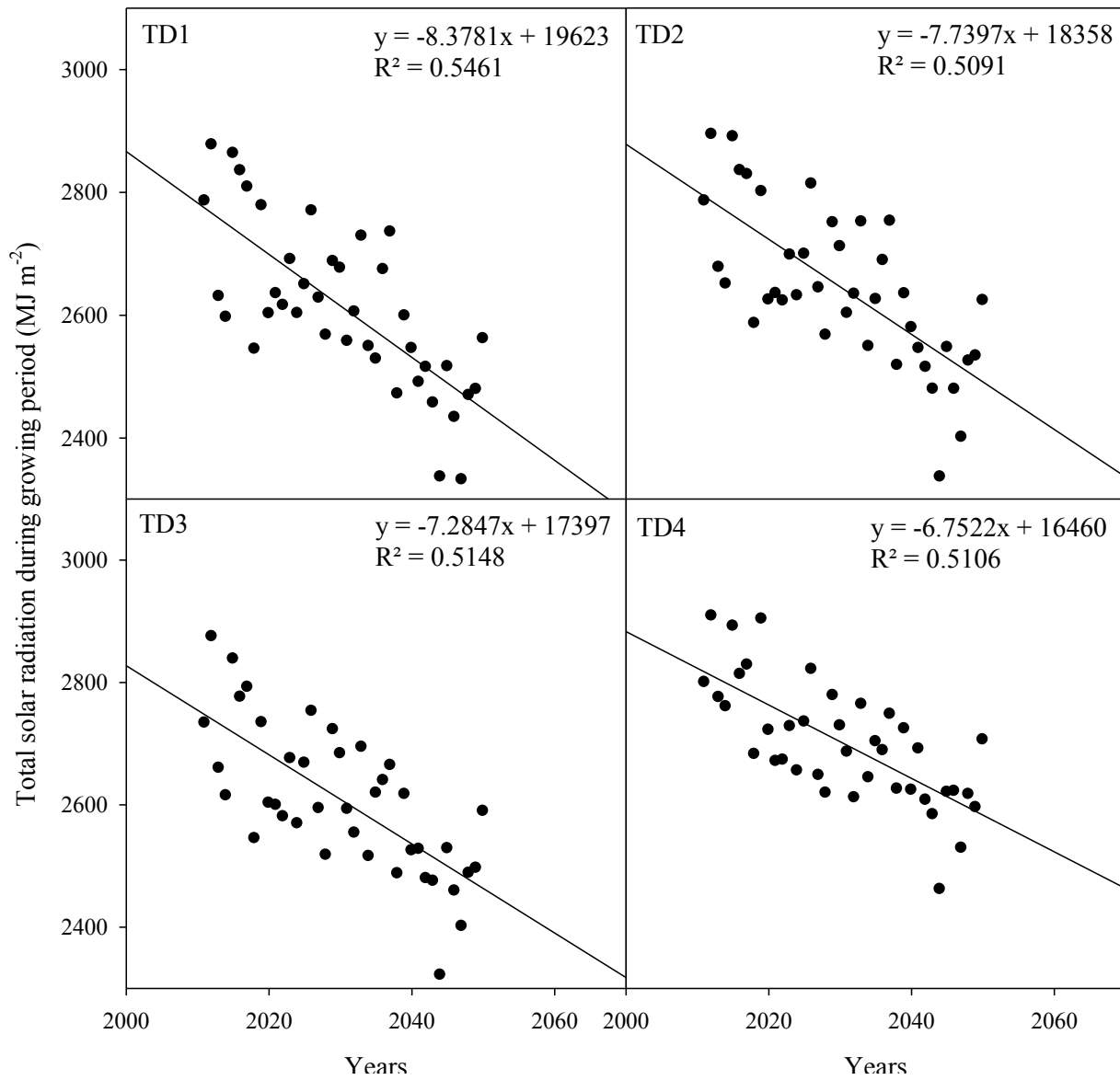


Figure 60: Changes in total solar radiation during growing period starting at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.

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### **4.3.2. Temperature variability in future years during tomato growing cycle**

Changing in average maximum temperature of growing cycle among future years was taking the tendency of slight increase for ENEA scenario and higher increase for MPI scenario. For ENEA scenario (Figure 61), average temperature of the season at TD1, 2, and 3 starts in 2011 with 23.3 and arrives to 23.7 in 2050, whereas at TD4 it starts in 2011 with 23.5 and arrives to 23.8 in 2050. For MPI scenario (Figure 62), the values of average maximum temperature for the growing cycle started at TD1, 2 and 3 will range from 21.7 in 2011 to 23.9 in 2050, and at TD4 it will be 21.9 °C in 2011 then it will increase to 24.2 °C in 2050.

Average minimum temperature for the growing cycle started among future years will change almost in the same tendency of maximum temperature. For ENEA scenario (Figure 63), the values of average maximum temperature for the growing cycle started at TD1, 2, 3 and 4 will range from 11.4 °C in 2011 to 12.2 °C in 2050. For MPI scenario (Figure 64), the values of average maximum temperature for the growing cycle started at TD1, 2, 3 and 4 will be higher with one degree from 2011 to 2050 than ENEA scenario having the range from 11.5 °C in 2011 to 13.3 °C in 2050.

By increasing temperature with about 1 degree using ENEA scenario and 2 degrees using MPI scenario in the period from 2011 to 2050, we will see in the coming figures how transplanting at different dates affected tomato growth and yield.

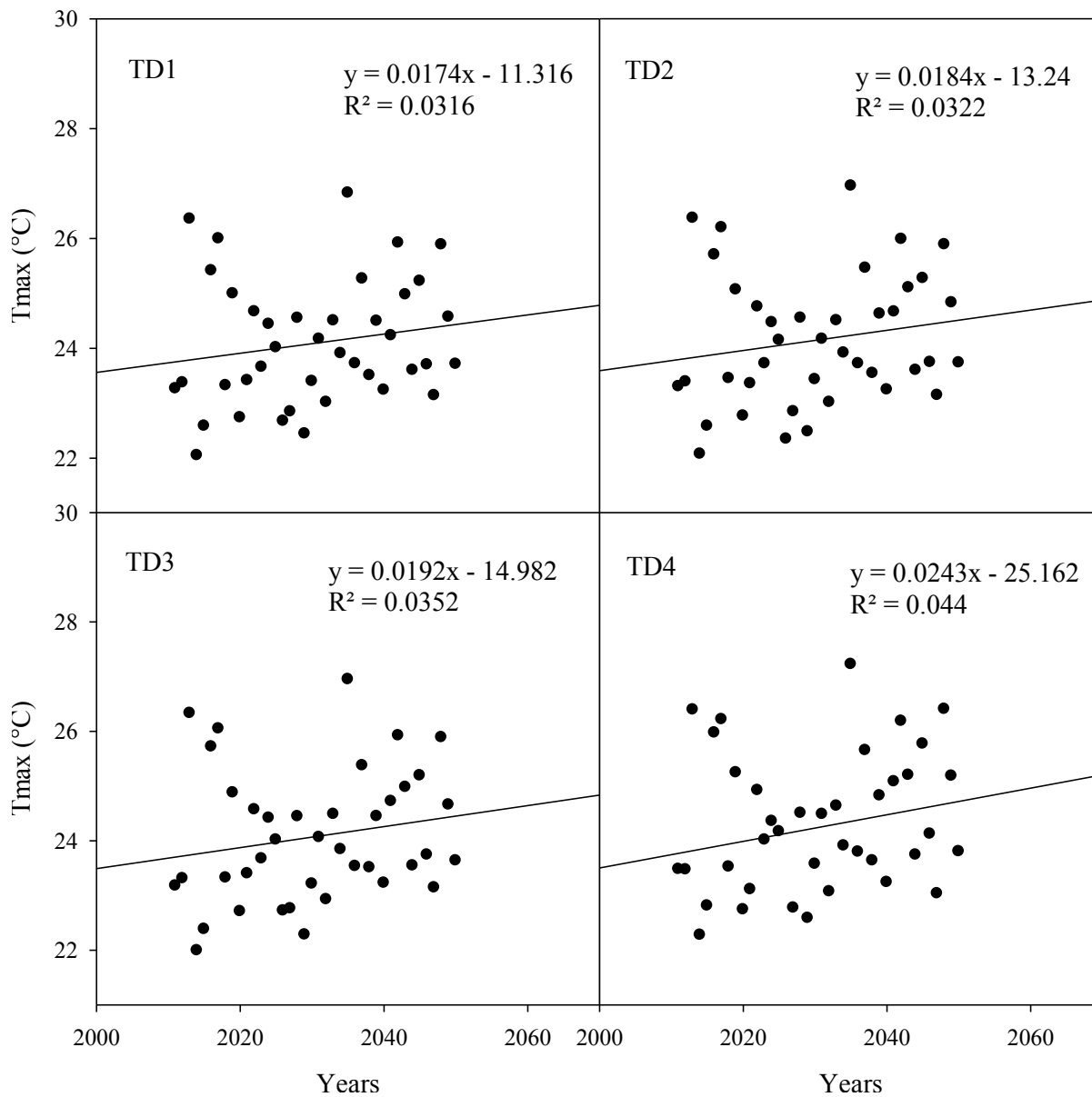


Figure 61: Changes in average maximum temperature during growing period starting at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.

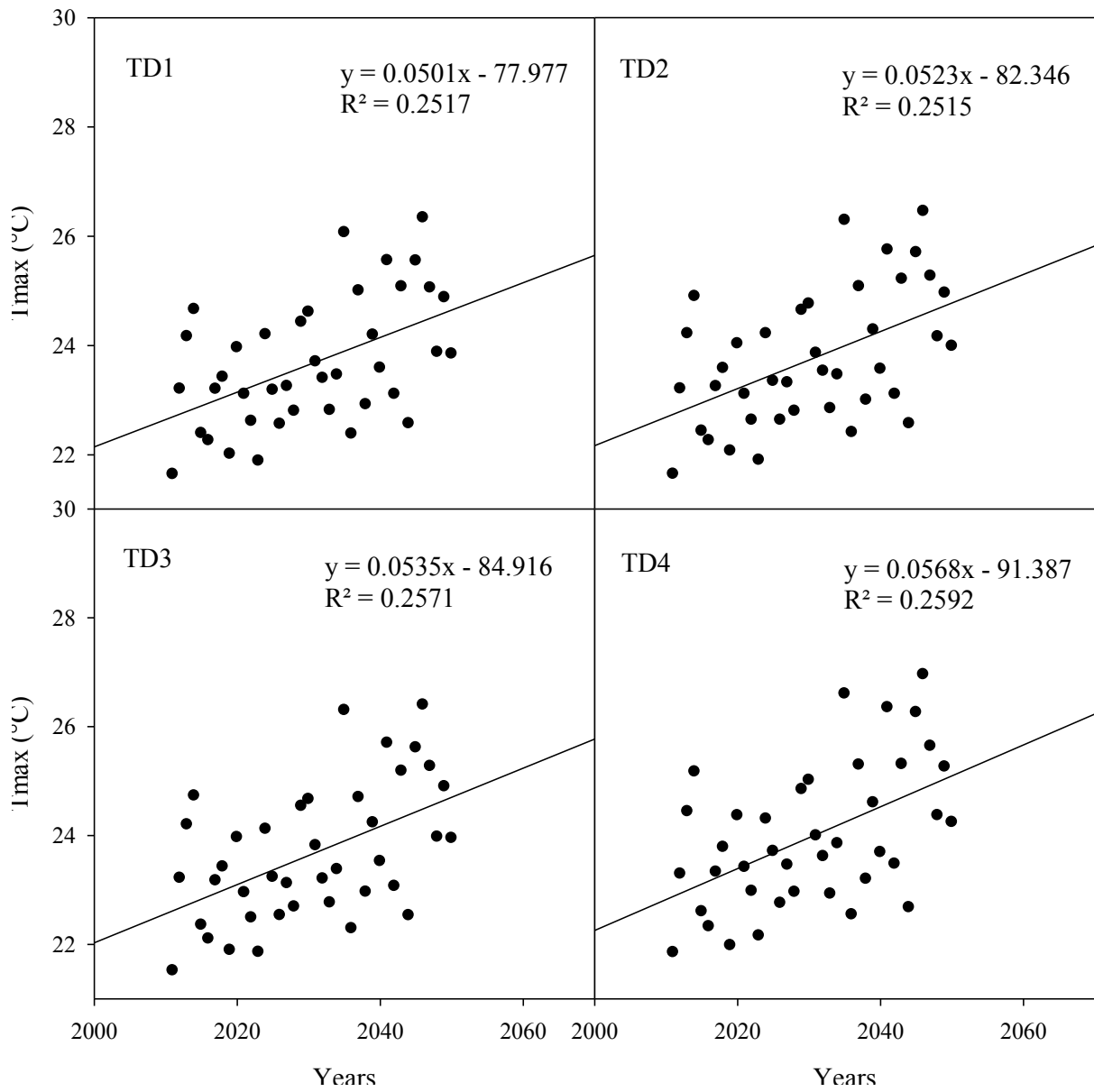


Figure 62: Changes in average maximum temperature during growing period starting at different transplanting dates (TD1, 2, 3, and 4) over future years from 2011 to 2050 for the MPI weather scenario.

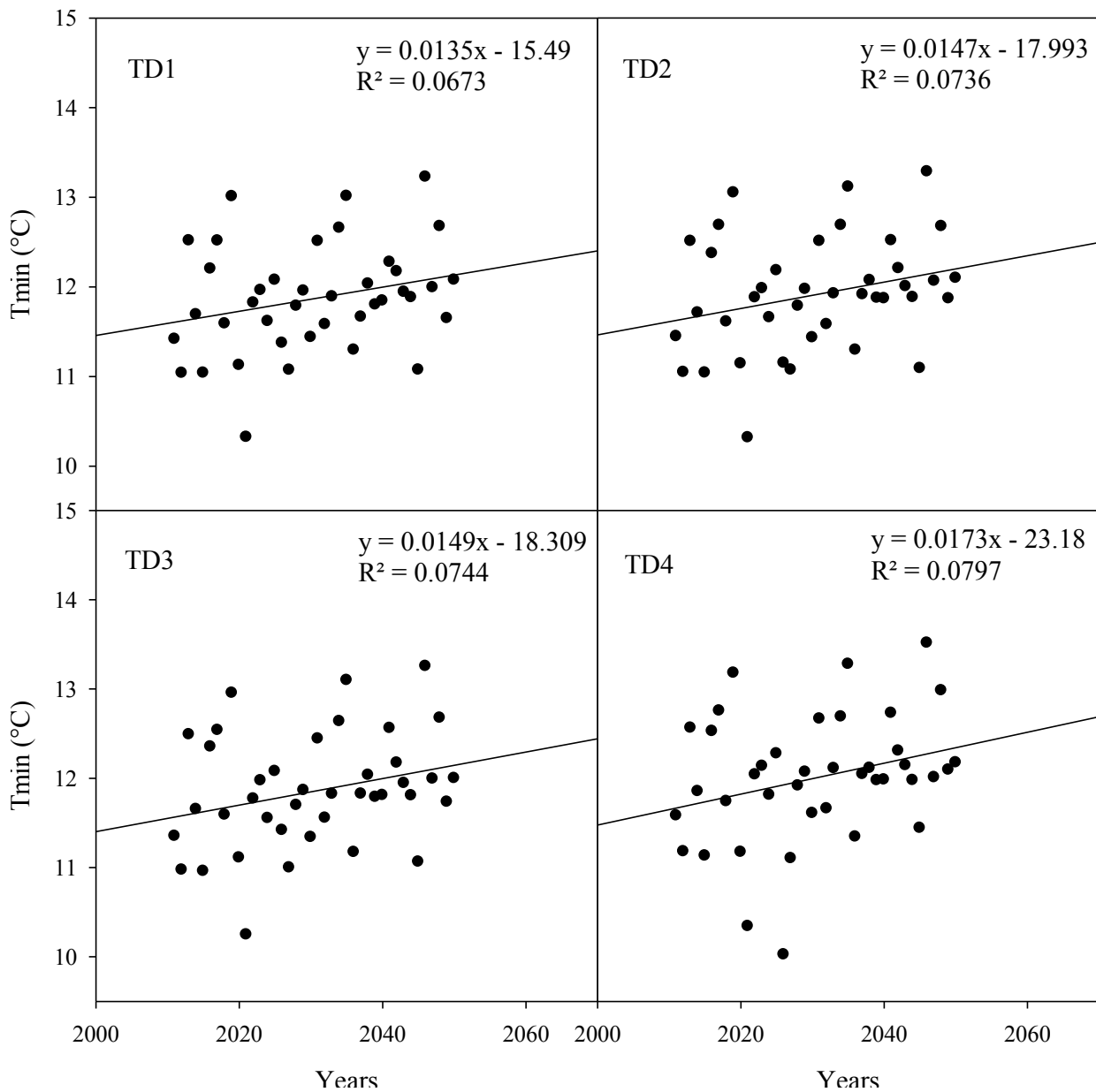


Figure 63: Changes in average minimum temperature during growing period starting at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.



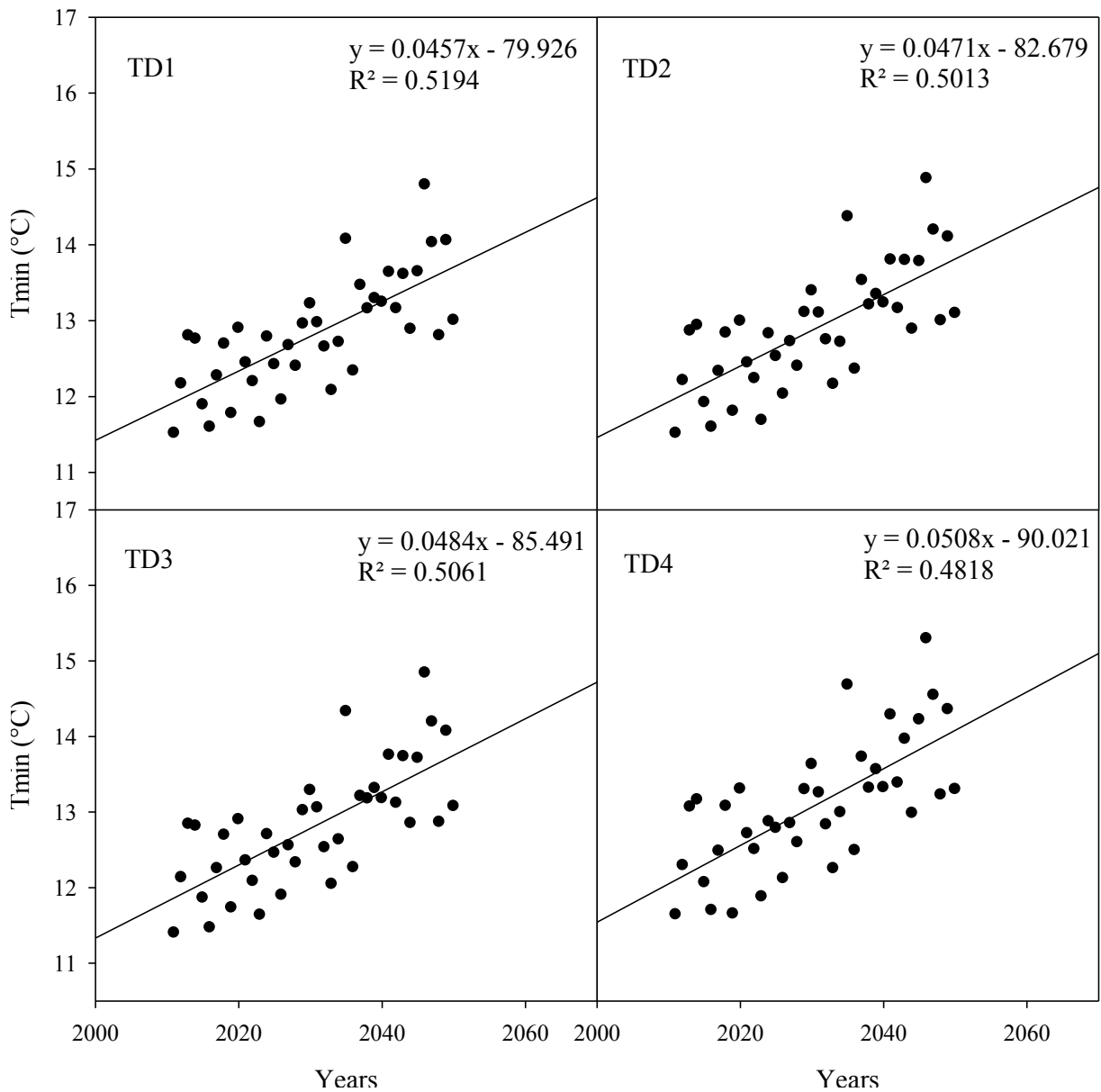


Figure 64: Changes in average minimum temperature during growing period starting at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.

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### **4.3.3. Precipitation variability in future years during tomato growing cycle**

Relation between future years and precipitation amount during the growing cycle will be almost stable in ENEA scenario. On the other hand, MPI scenario will decrease in a sharper way than ENEA scenario.

Regarding ENEA scenario, total precipitation during growing cycle will range from 200 to 700 mm for growing cycle started at TD1, from 200 to 750 mm for cycle started at TD2 and 3; and from 200 to 800 mm for cycle started at TD4. Moving from year 2011 to 2050, total amount of rain along the growing season for each year will be 500 mm in average (Figure 65). For MPI scenario, total precipitation during growing cycle will reduce from 316.6 mm in 2011 to 207.3 mm for growing cycle started at TD1, 2, 3 and 4. Total precipitation values during the growing cycle will not vary visibly among transplanting dates (Figure 66).

Although ENEA scenario had relatively higher probability and amount of rain, the need to increase amount of irrigation water will be higher than at MPI scenario, due to higher levels of evapotranspiration. By reduction in frequency and amount of rain for MPI scenario coupled with increases in temperature and solar radiation, there will be a need to increase irrigation frequency and amount during the growing cycle (Figure 67). This increment in irrigation amount will be different between the two scenarios due to differences in evapotranspiration rate between them. For ENEA scenario, evapotranspiration rate will be in higher levels than for MPI scenario, so the need for more amount of irrigation at ENEA scenario will be more than at MPI scenario. Plants will give better amount of yield at ENEA scenario but, at the same time, they will need more amount of irrigation water due to higher evapotranspiration levels (Figure 67). For farmers it will be recommended to keep plants at a good level of water requirements so they can maximize their benefits and reduce possible losses.

To run CSM-CROPGRO-Tomato model for future changes, simulation options were set to automatic irrigation when it is required, so plant growth outputs we will show later here are for the plants without influence of water stress, avoiding to irrigate at rainy days and having the maximum possible growth and yield amount under each studied weather conditions.

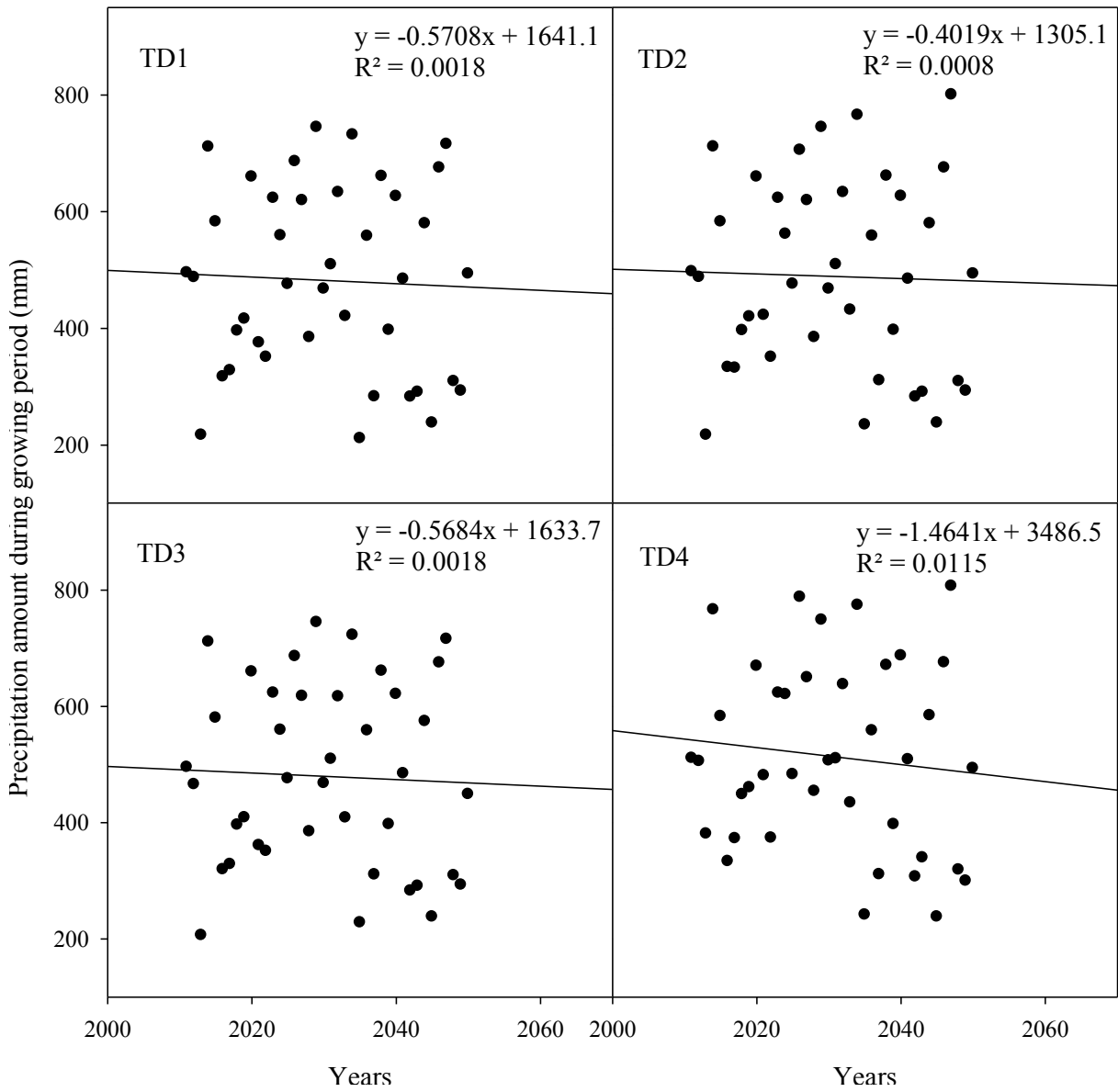


Figure 65: Changes in total annual precipitation during growing period starting at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.

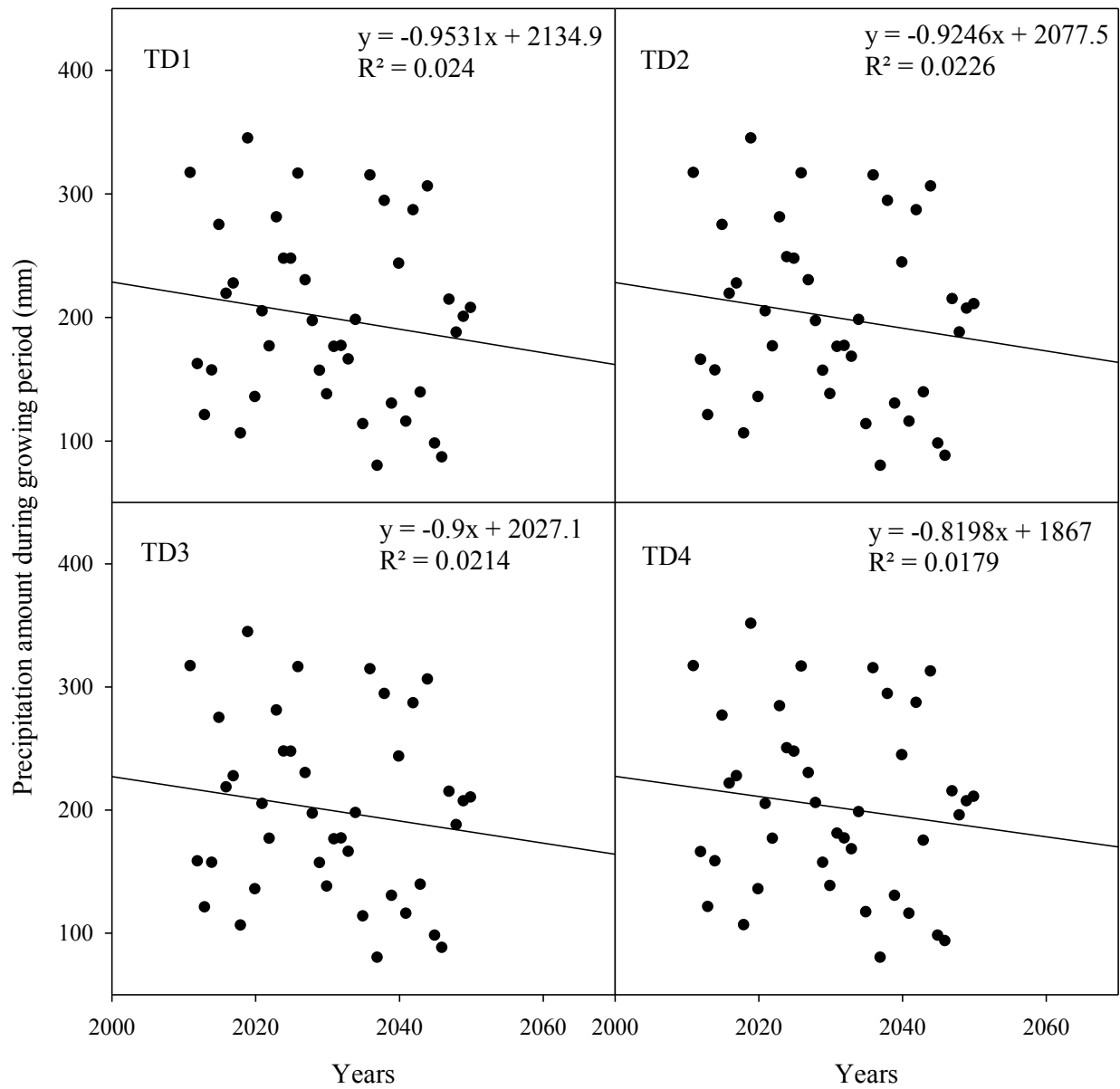


Figure 66: Changes in total solar radiation during growing period starting at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.

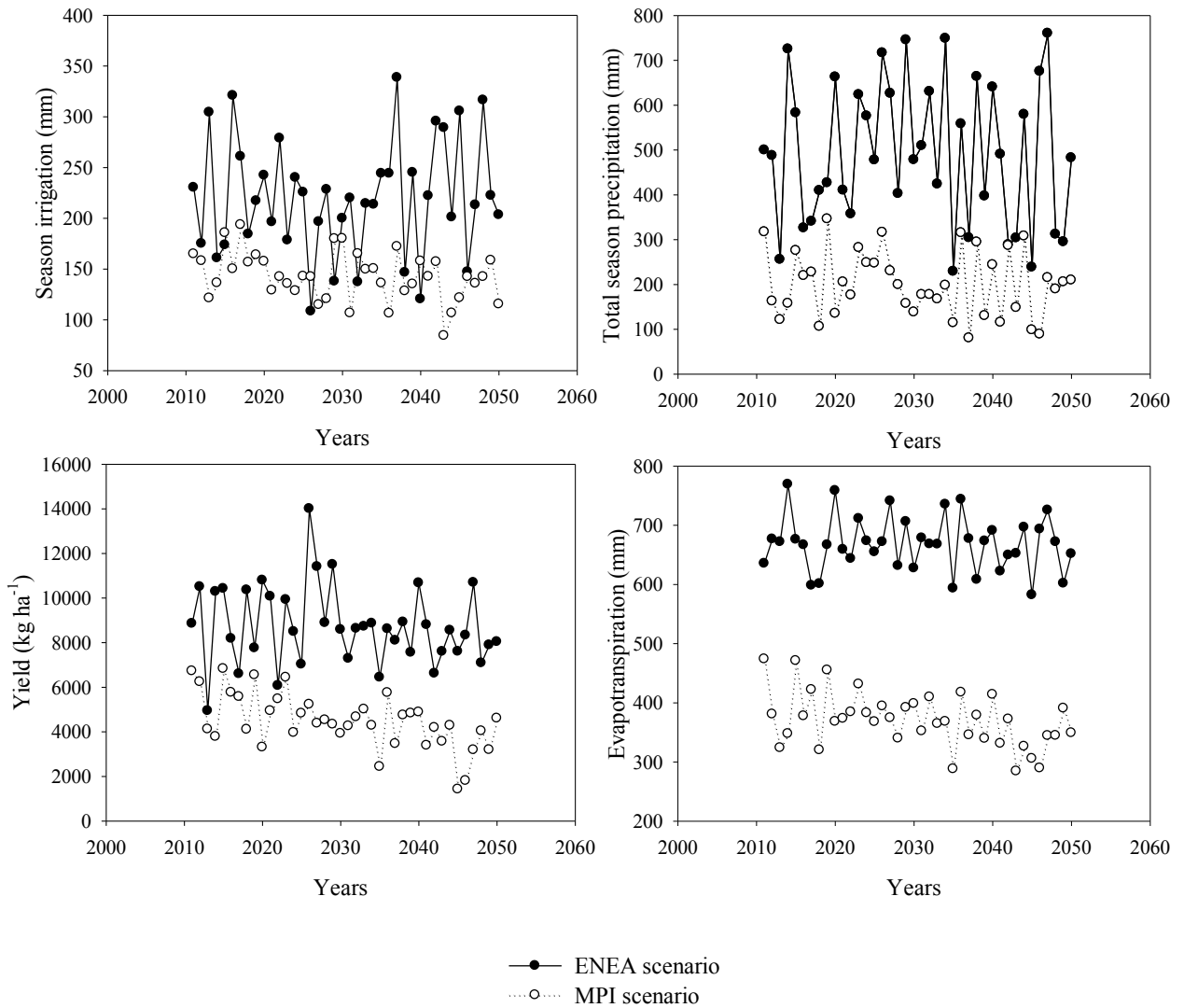


Figure 67: Changes in total season irrigation, total season precipitation, yield and evapotranspiration during growing period over future years from 2011 to 2050 for both ENEA the MPI weather scenarios.

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#### **4.3.4. Influence of future weather conditions on length of growing cycle of tomato plant**

The difference in growing cycle length by changing transplanting dates was clear and higher under MPI scenario weather conditions more than ENEA scenario weather conditions. This was due to difference in frequency and strength between both varieties which gave more influence for MPI scenario more than ENEA scenario (Figures 68 and 69).

Running future years from 2011 to 2050 with ENEA scenario, there will be a reduction in length of growing cycle giving 140 days in 2011 and 136 days in 2050 for TD1, 2 and 3; whereas for TD4, growing cycle will reduce from 107 days in 2011 to 102 days in 2050. With MPI scenario, on the other hand, growing cycle will reduce from 161 days in 2011 to 128 days in 2050 for TD1, 2 and 3; whereas for TD4, growing cycle will reduce from 126 days in 2011 to 100 days in 2050.

Length of growing cycle range under ENEA conditions was between 120 and 165 days at TD1, between 100 and 155 for TD2, and between 90 and 130 for TD3 and 4. Length of growing cycle range under MPI conditions was between 110 and 160 days at TD1, between 90 and 150 for TD2, and between 80 and 130 for TD3 and 4. The same results were obtained for both varieties under study.

Plants under ENEA scenario weather conditions had longer growing cycle than plants under MPI conditions. That was due to MPI scenario has relatively higher temperature and lower precipitation amount than ENEA scenarios. As high is the air temperature around plants, as fast it finishes its life cycle. In this case we recommend for farmers to control water requirements under MPI scenario conditions and for breeders to adapt new varieties more tolerant to heat stress.

Under both scenarios conditions, it was clear that increasing in temperature and evapotranspiration rates will affect negatively length of growing cycle. This will lead to less time for plants to make efficient metabolism and to form and develop fruits. In this way quality characteristics of fruits would be reduced i.e. soluble solids. For this reason, plants nutrition and water should be well balanced in order to minimize any negative effects on their growth, and subsequently on their fruits quality, as well as fruits quantity.

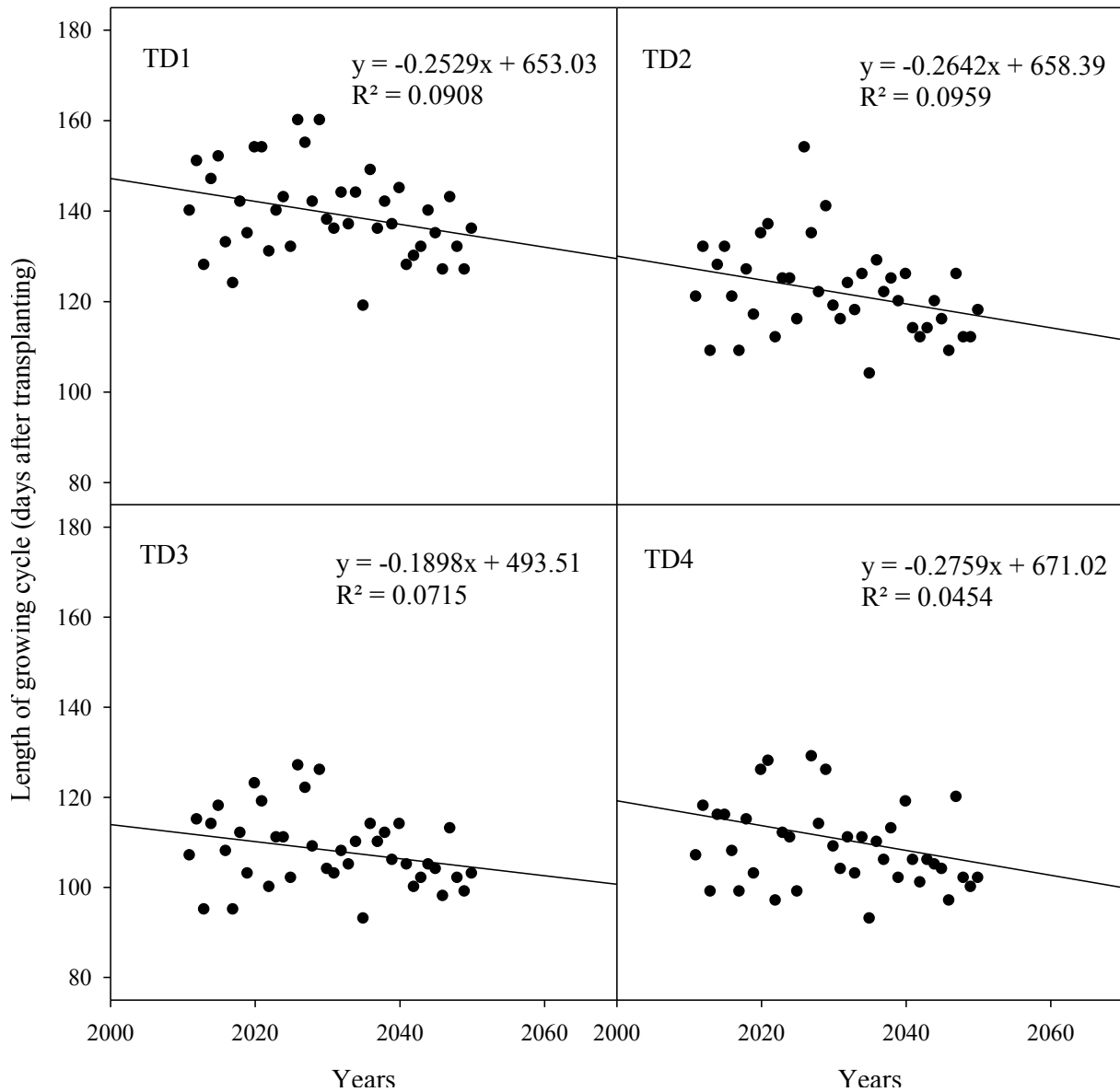


Figure 68: Changes in growing cycle's length of plants transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.

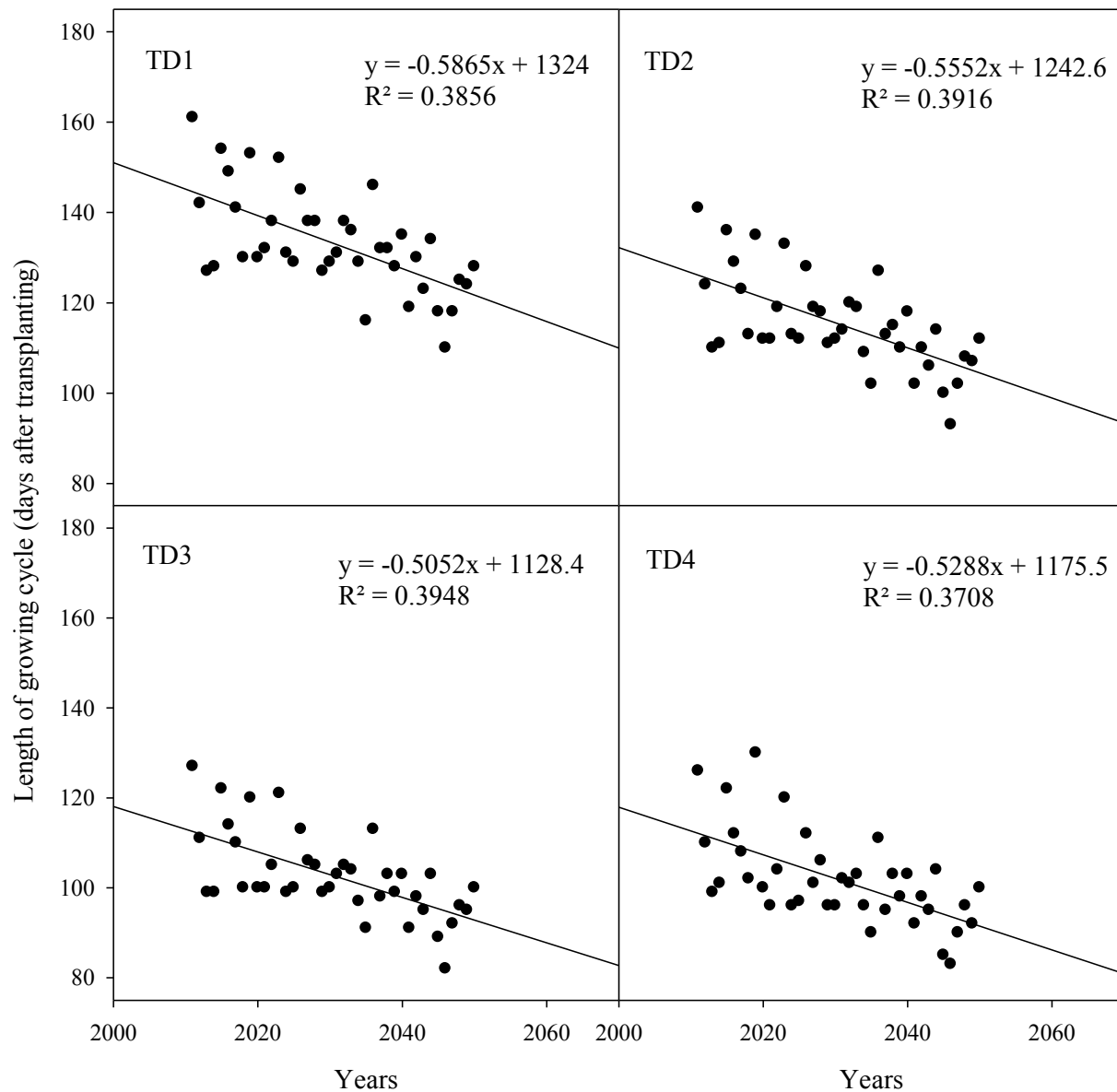


Figure 69: Changes in growing cycle's length of plants transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.



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#### **4.3.5. Influence of future weather conditions on total dry matter of tomato plants**

Plants of AUG variety under study gave higher resistance to ENEA scenario weather conditions more than NPT variety. Total plant dry weight of AUG variety under ENEA weather conditions was almost stable during future years from 2011 to 2050 when transplanting dates was early (TD1, 2 and 3) giving total dry matter of 16208 kg ha<sup>-1</sup> in 2011 and 14830 kg ha<sup>-1</sup> in 2050. Transplanting plants at late transplanting (TD3 and 4) gave a negative effect on total plant dry matter giving total dry matter of 16546 kg ha<sup>-1</sup> in 2011 and 15201 kg ha<sup>-1</sup> in 2050. AUG plants under such scenario conditions gave total dry weight range from 13500 to 22500 kg ha<sup>-1</sup>(Figure 70).

MPI scenario weather conditions gave a strong effect on total plants dry weight of AUG variety, having 11613 kg ha<sup>-1</sup> in 2011 and 8819 kg ha<sup>-1</sup> in 2050 at TD1, and having 9956 kg ha<sup>-1</sup> in 2011 and 7309 kg ha<sup>-1</sup> in 2050 at TD4. AUG plants under that scenario conditions will give total dry weight ranges from 4000 to 13000 kg ha<sup>-1</sup> (Figure 72).

For NPT plants, the response was almost the same as AUG for the total plant dry matter. Using ENEA scenario weather conditions, plants will be influenced slightly at TD1, giving total dry weight of 16673 kg ha<sup>-1</sup> in 2011 and 15418 kg ha<sup>-1</sup> in 2050. At TD4, total plant dry matter will range from 17393 kg ha<sup>-1</sup> in 2011 to 16698 kg ha<sup>-1</sup> in 2050. In this way we will have better influence over years for early transplanting, reducing total dry mater values from 2011 to 2050 (Figure 71).

NPT variety under MPI scenario weather conditions will have sharper negative influence than plants under conditions of ENEA scenario. At TD1, plants will give total dry weight of 11731 kg ha<sup>-1</sup> in 2011 and 9359 kg ha<sup>-1</sup> in 2050. At TD4, total plant dry matter will range from 11968 kg ha<sup>-1</sup> in 2011 to 8459 kg ha<sup>-1</sup> in 2050. Total plants dry weight will range from 6000 to 14000 kg ha<sup>-1</sup> with lower plant weight under weather conditions of late transplanting (Figure 73).

As we can observe, plants weight were influenced by changes in weather conditions over the coming years. This influence was clearer on the plants transplanted lately in the growing season, having higher temperature during transplanting shock period. These plants

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continues to grow in a weak manner, then at the end of the growing cycle they will have low quantity of fruits and smaller fruits size. These bad influences can be avoided by anticipate transplanting early in the season and giving plants regularly their requirements of water and nutrition. Breeders can also help in this regard by producing heat-resistant and drought-resistant varieties which could help farmers in developing their production.

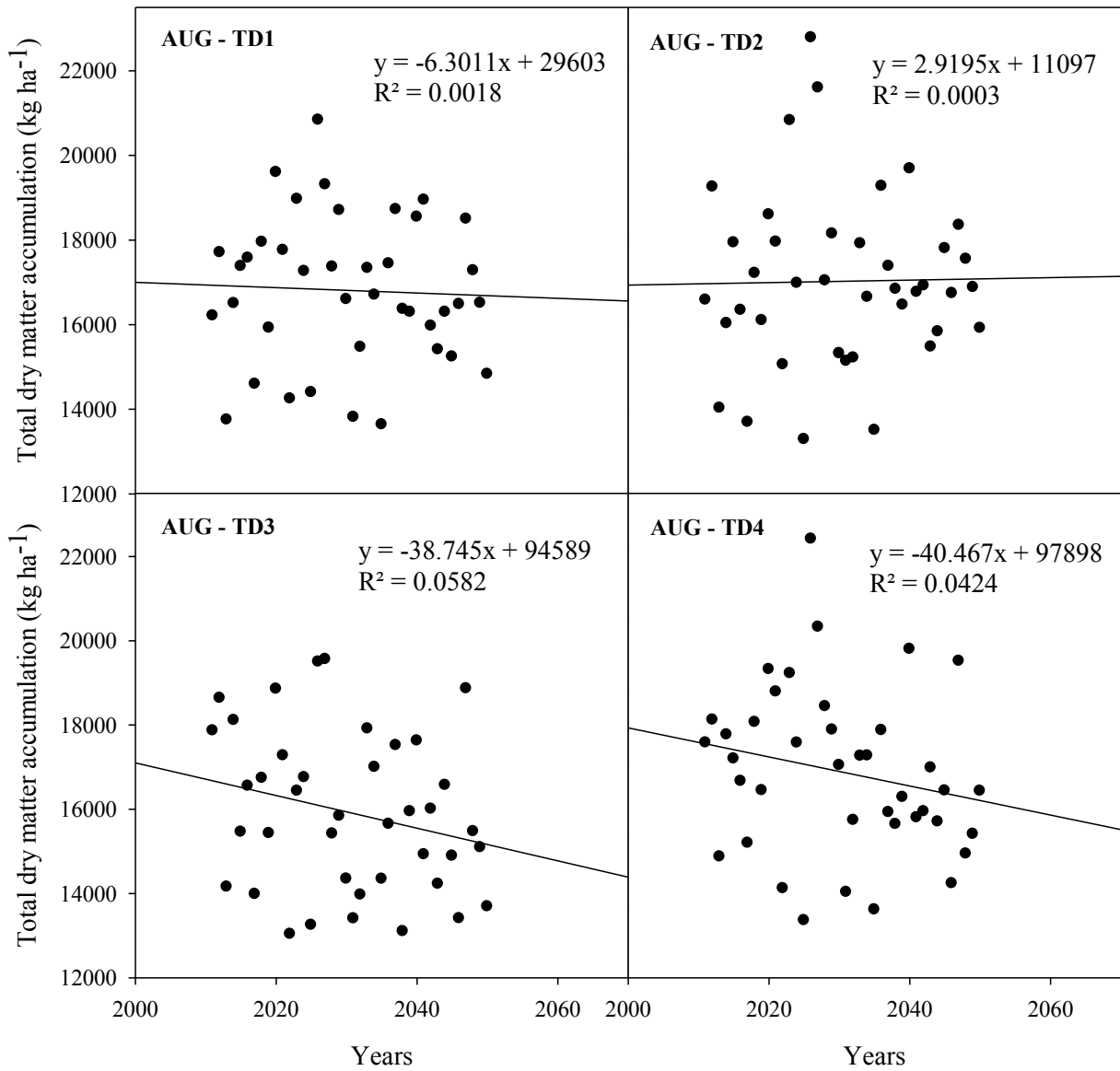


Figure 70: Changes in total plant dry weight for plants of AUG variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.

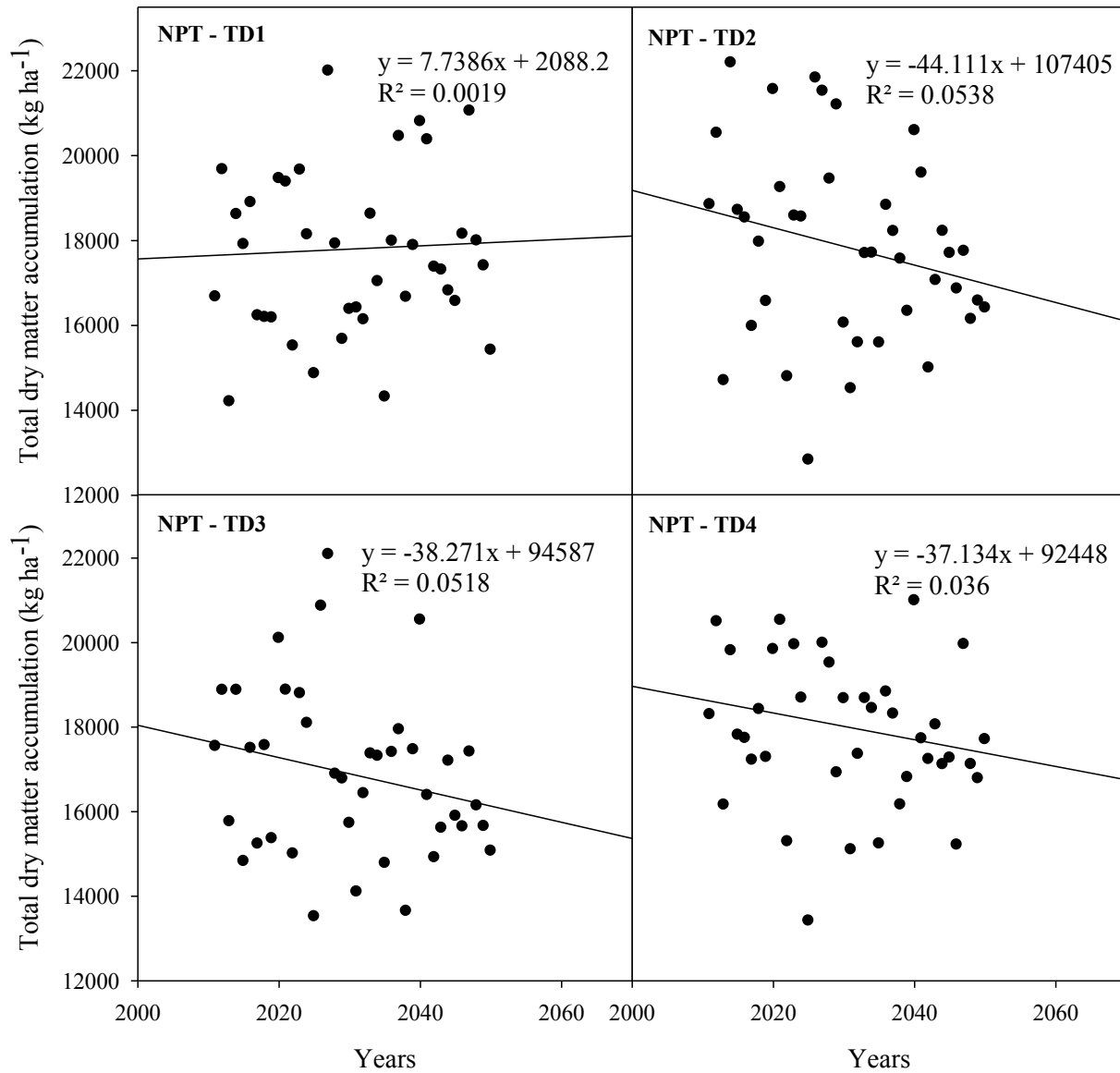


Figure 71: Changes in total plant dry weight for plants of NPT variety transplanted at different transplanting dates (TD1, 2, 3, and 4) over future years from 2011 to 2050 for the ENEA weather scenario.

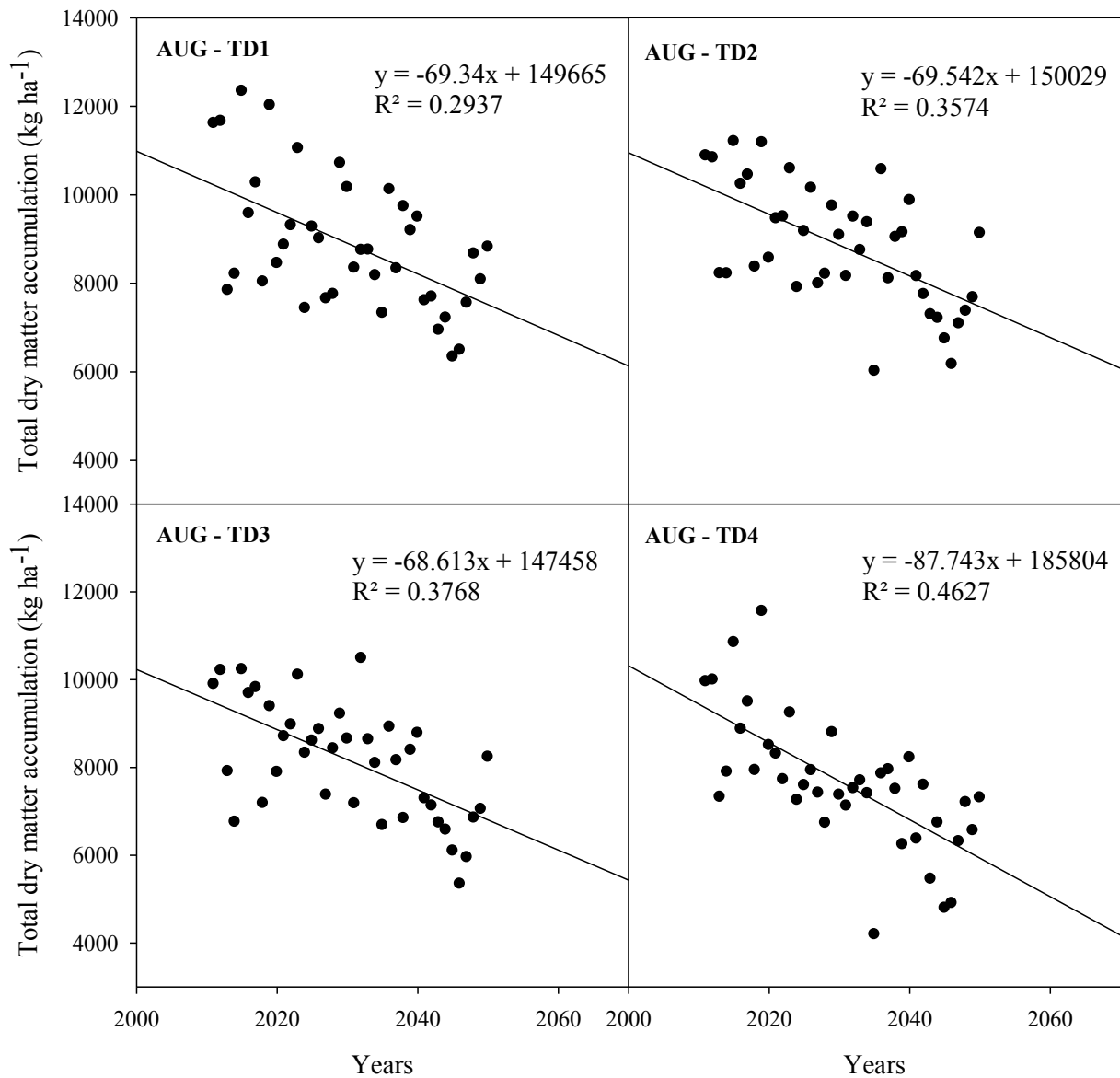


Figure 72: Changes in total plant dry weight for plants of AUG variety transplanted at different transplanting dates (TD1, 2, 3, and 4) over future years from 2011 to 2050 for the MPI weather scenario.

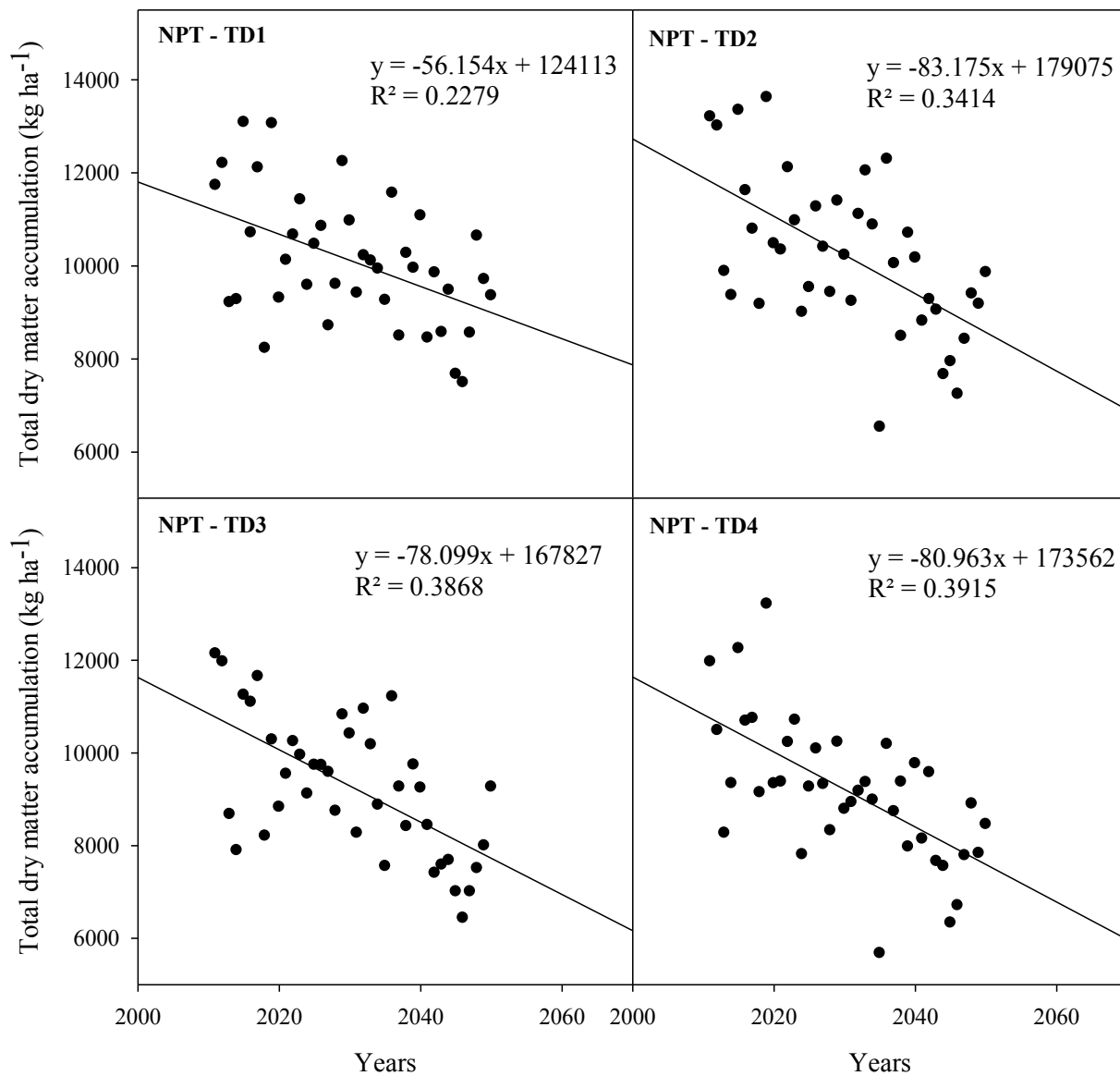


Figure 73: Changes in total plant dry weight for plants of NPT variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.

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#### 4.3.6. Influence of future weather conditions on yield of tomato plants

Observing yield of AUG variety under ENEA scenario weather conditions, we can see that yield was affected negatively moving through years from 2011 to 2050. Plants under ENEA scenario weather conditions will give 173156 kg ha<sup>-1</sup> in 2011 and 161547 kg ha<sup>-1</sup> in 2050 at TD1, whereas at TD4 it will give 181480 kg ha<sup>-1</sup> in 2011 and 152768 kg ha<sup>-1</sup> in 2050. Yield production under different transplanting dates will range from 100000 to 250000 kg ha<sup>-1</sup> (Figure 74).

AUG plants under MPI scenario weather conditions will have sharper reduction in yield over years for all transplanting dates. Plants under this scenario weather conditions will give 147835 kg ha<sup>-1</sup> in 2011 and 94486 kg ha<sup>-1</sup> in 2050 at TD1, whereas at TD4 it will give 121916 kg ha<sup>-1</sup> in 2011 and 82059 kg ha<sup>-1</sup> in 2050. Plants under this scenario conditions will give yield ranging from 40000 to 140000 kg ha<sup>-1</sup> (Figure 76).

Plants of NPT variety under ENEA scenario weather conditions, we can see that yield was affected negatively moving through years from 2011 to 2050. Plants under this scenario weather conditions will give 183563 kg ha<sup>-1</sup> in 2011 and 167298 kg ha<sup>-1</sup> in 2050 at TD1, whereas at TD4 it will give 196721 kg ha<sup>-1</sup> in 2011 and 169299 kg ha<sup>-1</sup> in 2050. Yield production under different transplanting dates will range from 100000 to 300000 kg ha<sup>-1</sup> (Figure 75).

NPT plants under MPI scenario weather conditions will have sharper reduction in yield over years for all transplanting dates. Plants under this scenario weather conditions will give 155715 kg ha<sup>-1</sup> in 2011 and 102953 kg ha<sup>-1</sup> in 2050 at TD1, whereas at TD4 it will give 146620 kg ha<sup>-1</sup> in 2011 and 90413 kg ha<sup>-1</sup> in 2050. Plants under this scenario conditions will give yield ranging from 40000 to 180000 kg ha<sup>-1</sup> (Figure 77).

From these model outputs I was clear that quantity of fruits was affected by changing in weather conditions over the coming 40 years. Having optimum management of plants nutrition and water requirements would increase yield quantity and plant growth in general. Transplanting seedlings early in the season will have also its positive influence on plants growth and consequently their production of fruits.

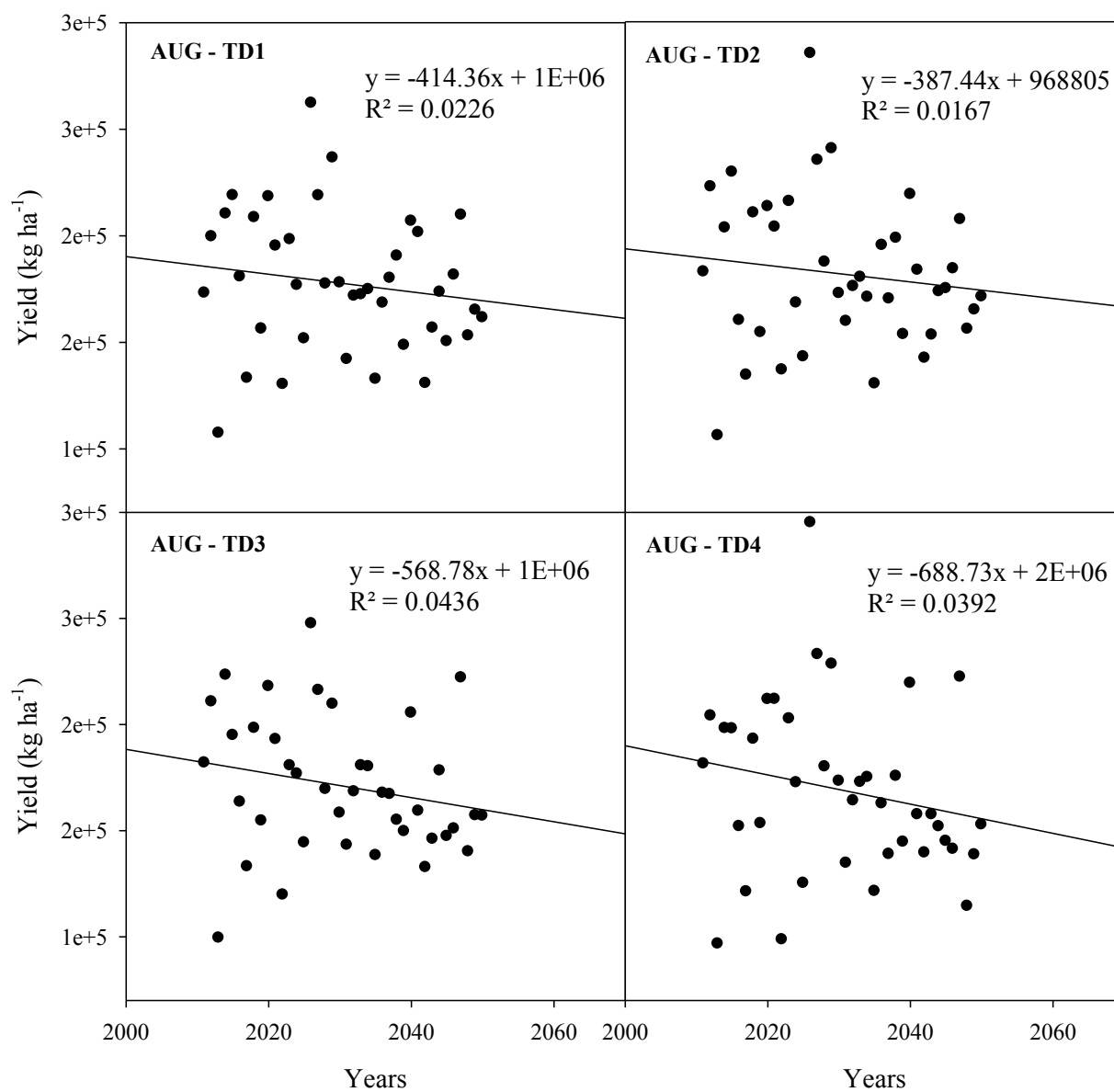


Figure 74: Changes in total fruits fresh weight for plants of AUG variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.



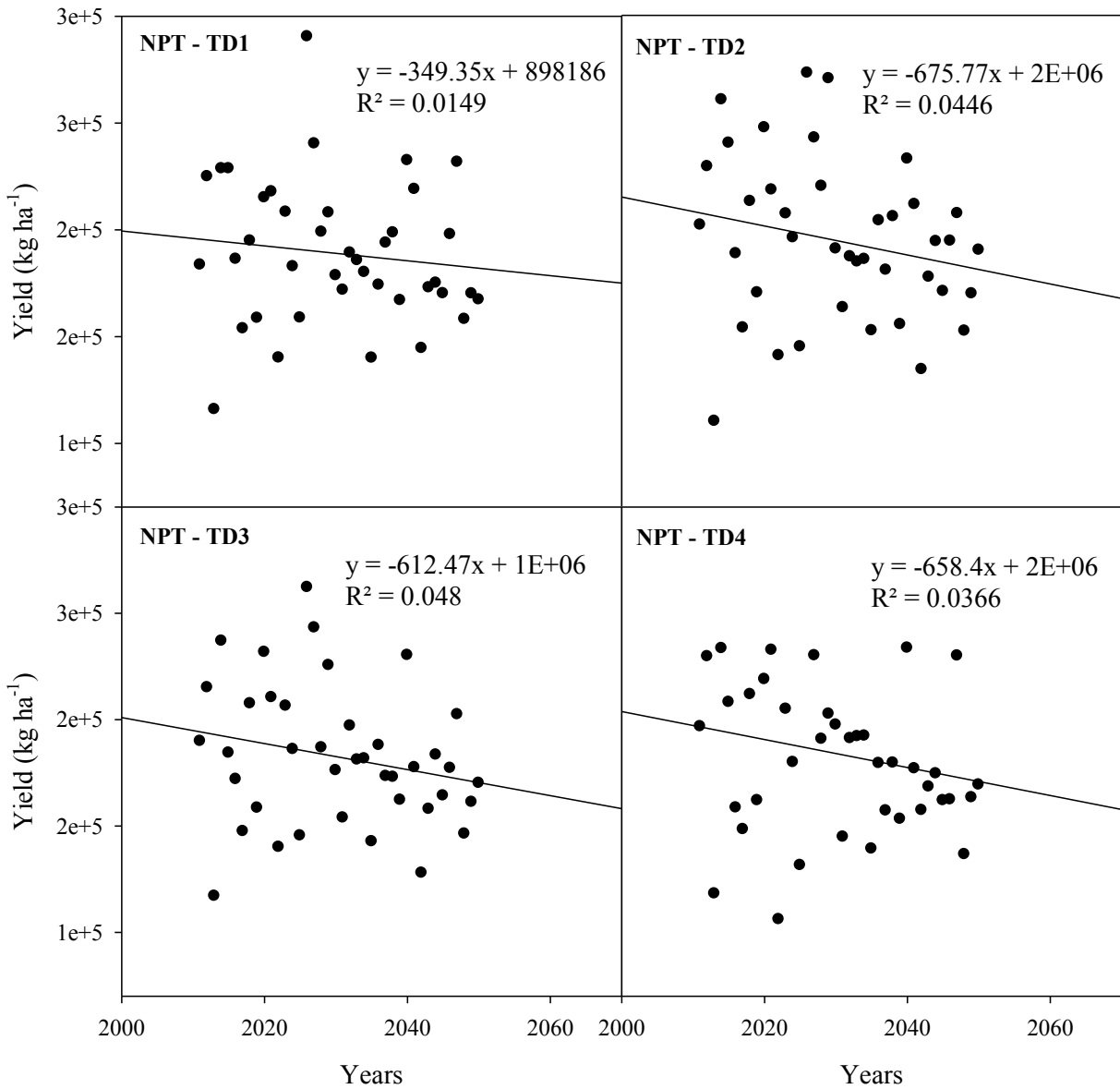


Figure 75: Changes in total fruits fresh weight for plants of NPT variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.

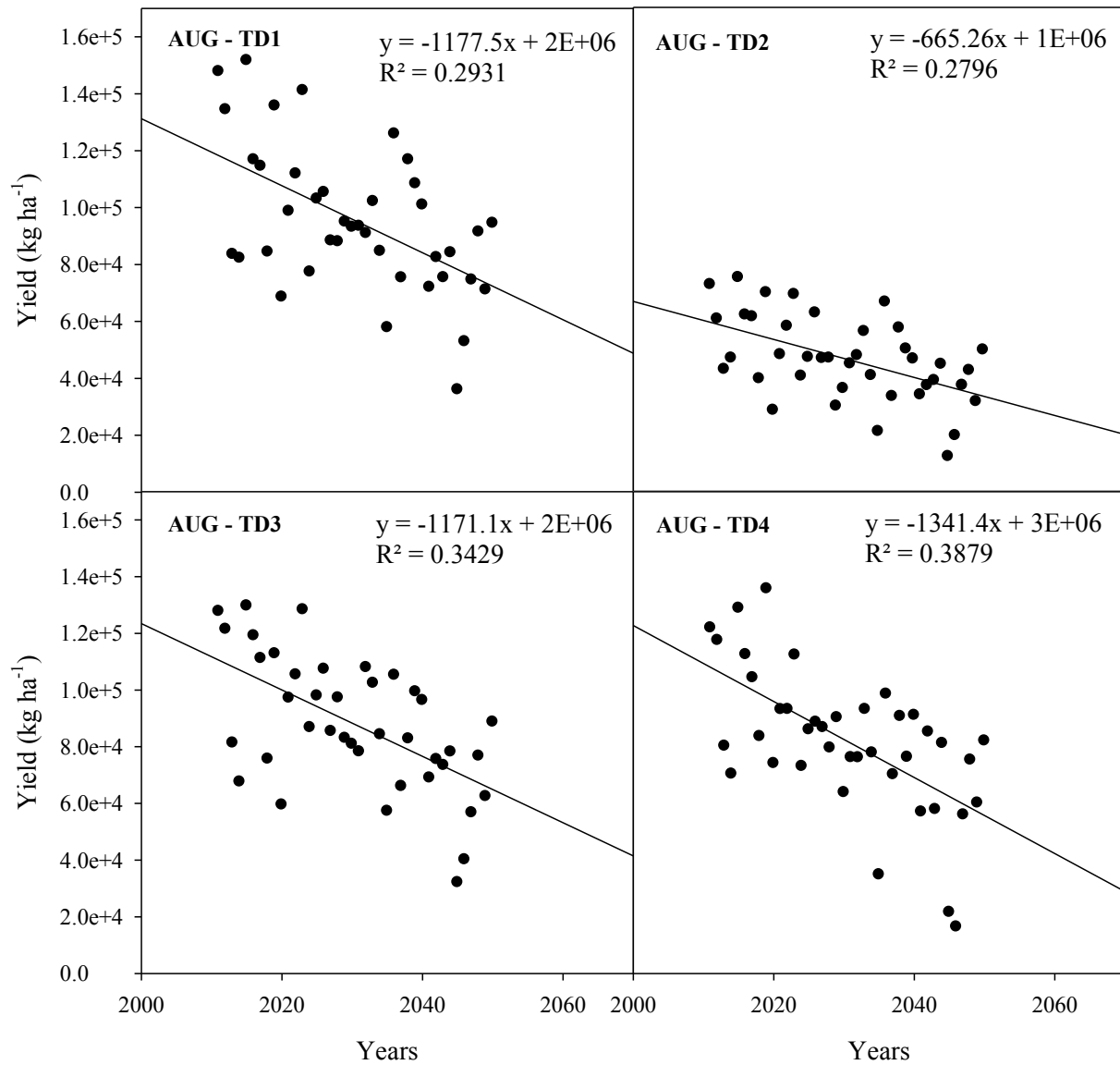


Figure 76: Changes in total fruits fresh weight for plants of AUG variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.

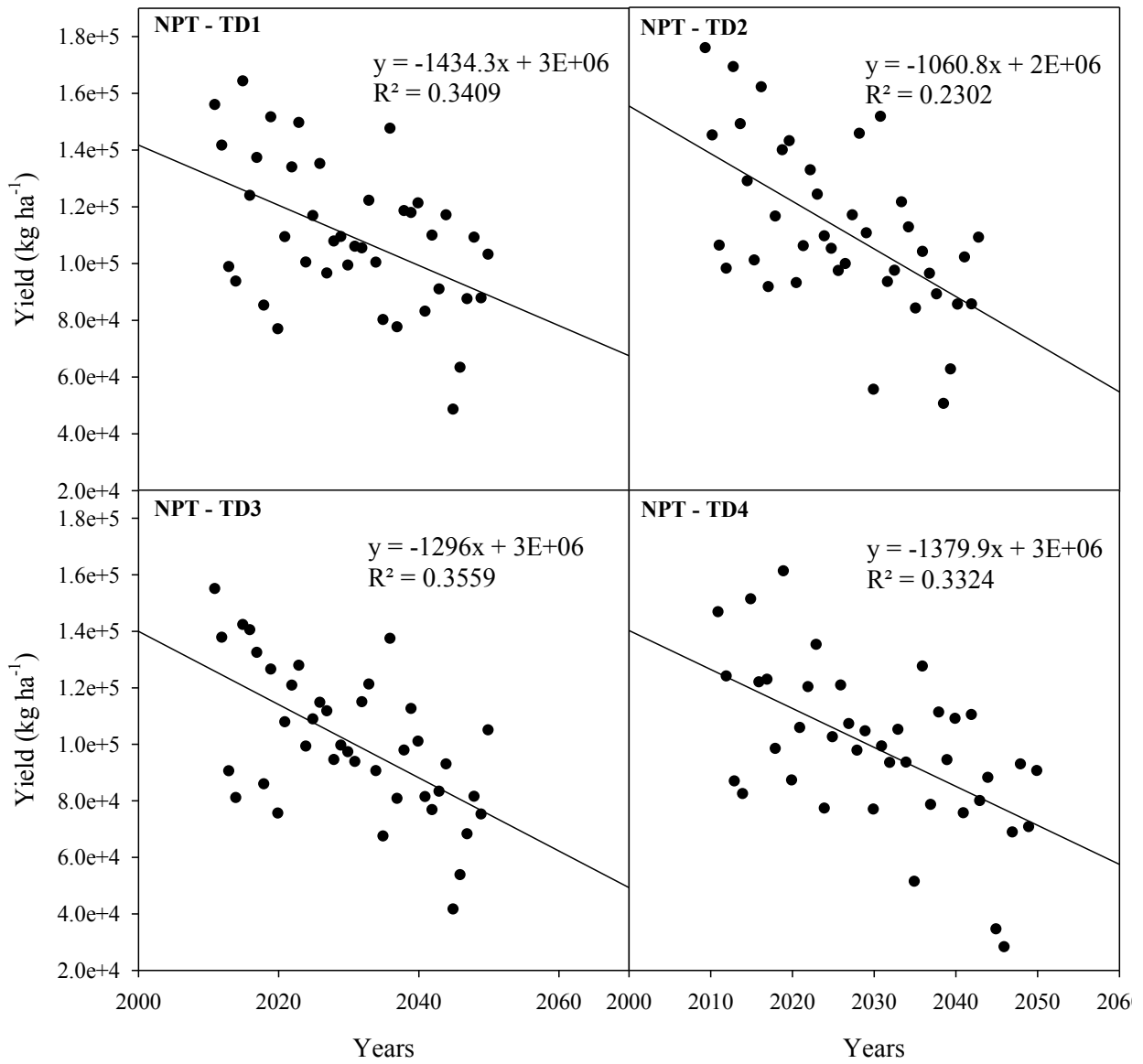


Figure 77: Changes in total fruits fresh weight for plants of NPT variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.

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#### **4.3.7. Influence of future weather conditions on harvest index of tomato plants**

Harvest index is a parameter shows the relationship between plant's weight and its amount of fruits produced per season. This relation is considered for vegetable plants to have an indication of the potential productivity per plant. Observing harvest index of AUG variety under ENEA scenario weather conditions, we can see that harvest index was affected negatively moving through years from 2011 to 2050. Plants under this scenario weather conditions will give harvest index o 0.54 in 2011 and 0.55 in 2050 at TD1, whereas at TD4 it will give 0.55 in 2011 and 0.52 in 2050 (Figure 78).

Plants of AUG variety under MPI scenario weather conditions will have sharper reduction in harvest index over years for all transplanting dates. Plants under this scenario weather conditions will give harvest index o 0.64 in 2011 and 0.54 in 2050 at TD1, whereas at TD4 it will give 0.61 in 2011 and 0.56 in 2050. Plants under this scenario conditions will give harvest index ranging from 0.35 to 0.65 (Figure 80).

Plants of NPT variety under ENEA scenario weather conditions, we can see that harvest index was affected negatively moving through years from 2011 to 2050. Plants under this scenario weather conditions will give harvest index o 0.55 in both 2011 and 2050 years at TD1, whereas at TD4 it will give 0.56 in 2011 and 0.53 in 2050. Harvest index production under different transplanting dates will range from 0.38 to 0.68 (Figure 79).

NPT plants under MPI scenario weather conditions will have sharper reduction in harvest index over years for all transplanting dates. Plants under this scenario weather conditions will give harvest index o 0.67 in 2011 and 0.55 in 2050 at TD1, whereas at TD4 it will give 0.62 in 2011 and 0.53 in 2050. Plants under this scenario conditions will give harvest index ranging from 0.40 to 0.68 (Figure 81).

Plants were influenced by changing transplanting dates under weather condition of each scenario. Early transplanting will influence harvest index positively as it could increase plants efficiency in fruits formation and development, or at least stabilize harvest index over the coming 40 years. This positive influence is due to lower air temperature at time of transplanting, so the plants recover transplanting shock in a better way and later their growth

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will be healthy enough to carry reasonable amount of fruits. Farmers are advised to keep their transplanting early in the season. Breeders' efforts are needed in order to obtain new processing tomato varieties more resistant to heat stress represented by evapotranspiration levels.

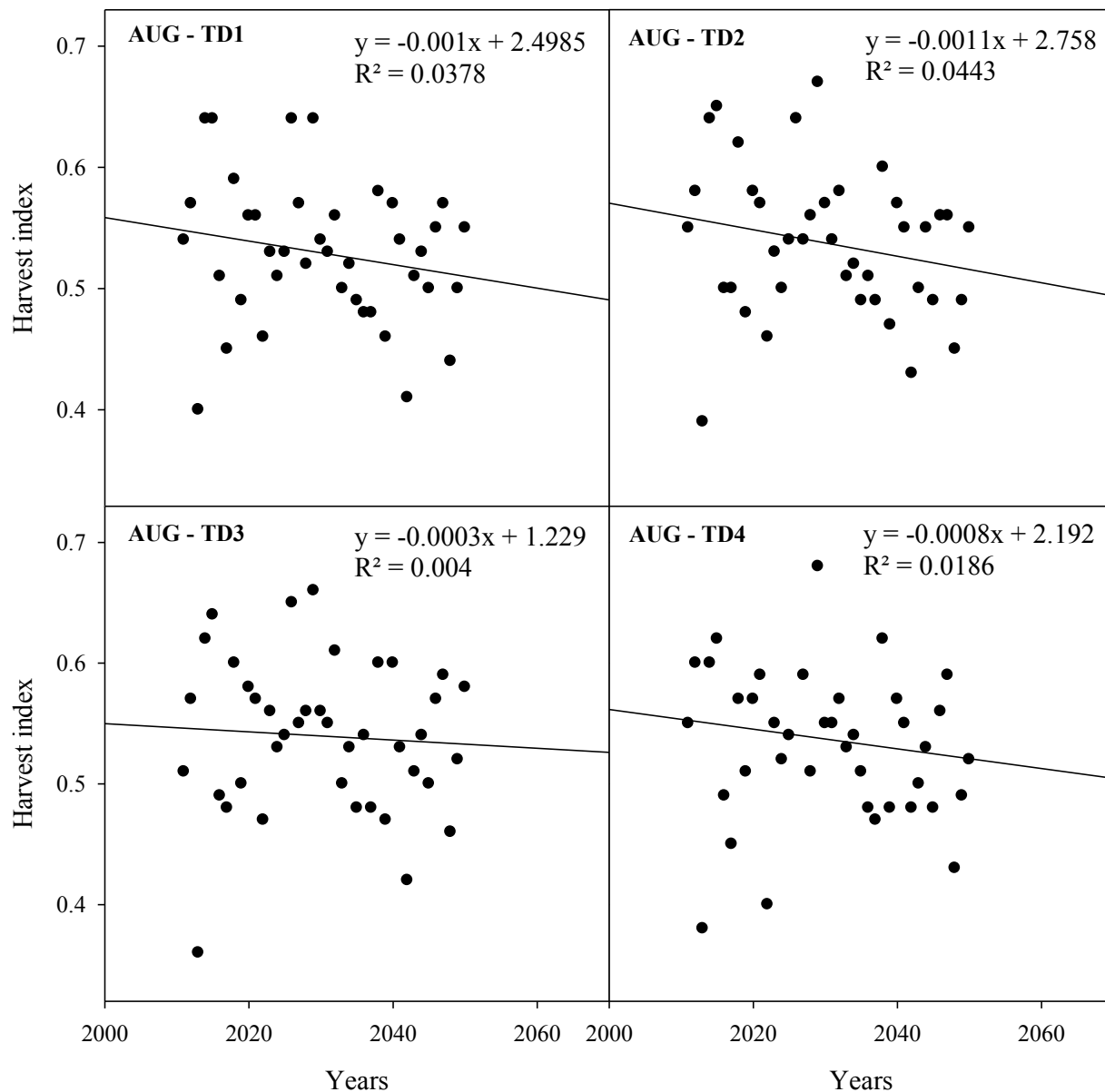


Figure 78: Changes in harvest index for plants of AUG variety transplanted at different transplanting dates (TD1, 2, 3, and 4) over future years from 2011 to 2050 for the ENEA weather scenario.

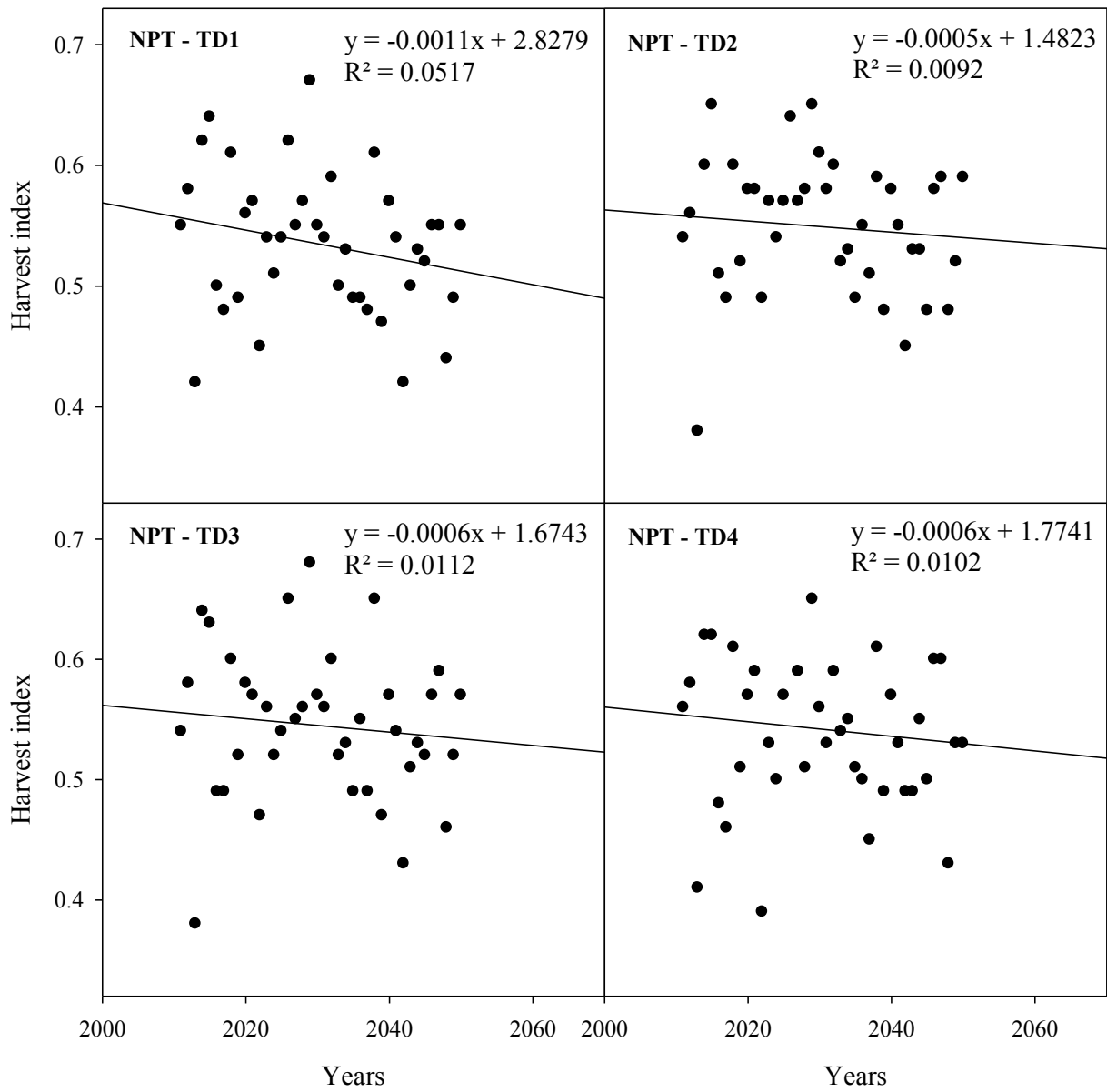


Figure 79: Changes in harvest index for plants of NPT variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the ENEA weather scenario.

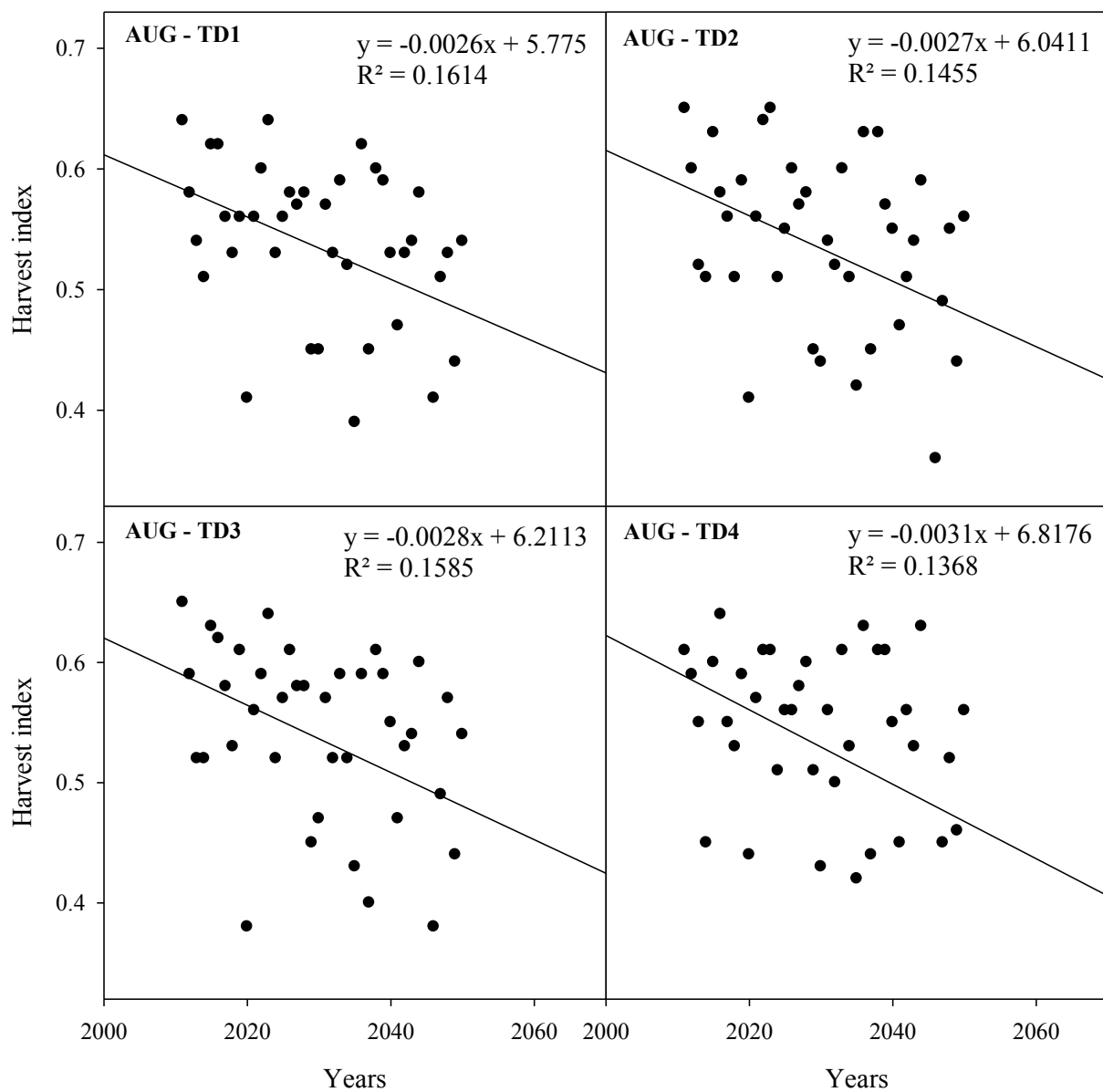


Figure 80: Changes in harvest index for plants of AUG variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.



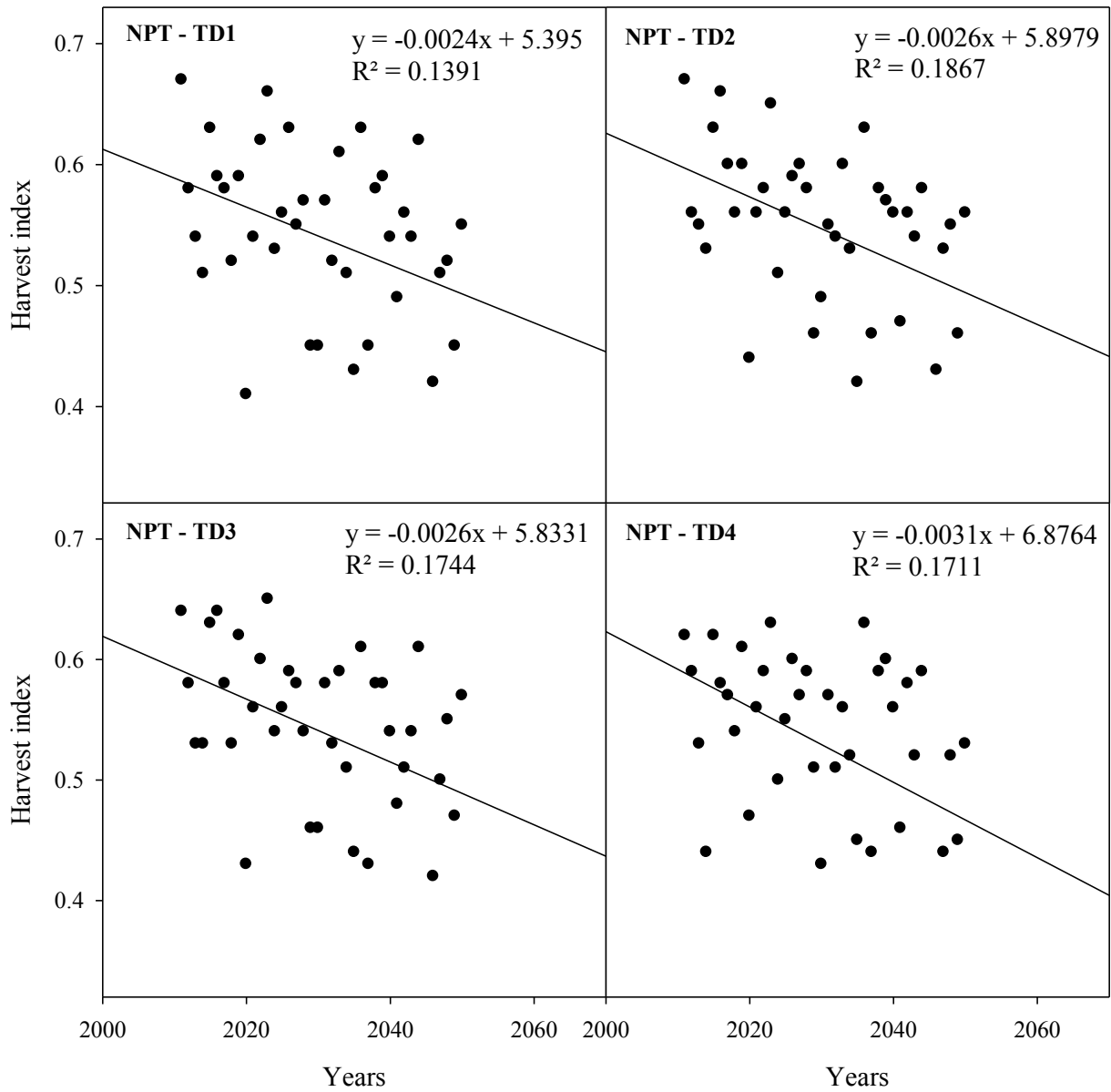


Figure 81: Changes in harvest index for plants of NPT variety transplanted at different transplanting dates (TD1, 2, 3, and 4).over future years from 2011 to 2050 for the MPI weather scenario.

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## 4.4. Conclusion

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Calibrated and validated CSM-CROPGRO-Tomato model was used to simulate growth of two field-grown processing tomato varieties under future climate variability. Length of growing cycle, total plant dry matter, yield and harvest index were the parameters evaluated using 40 years of future daily weather data obtained by two different downscaling methods of GCMs. Scenarios used in this study were obtained based on A1B scenario of IPCC-SRES scenario.

Global solar radiation, maximum and minimum temperature, and precipitation will affect growing cycle length, having shorter growing cycle by increasing temperature and reducing precipitation frequency and amount. Total plant dry matter, yield and harvest index will be affected negatively by season average maximum and minimum temperature, as well as solar radiation, especially at late transplanting dates through changes in evapotranspiration levels over years. As long was the growing cycle, as low was temperature average during the growing season. Although higher probability and amount of precipitation using ENEA scenario, amount of irrigation needed under ENEA scenario weather conditions will be higher than MPI scenario weather conditions. That increasing in irrigation amount will be due to high evapotranspiration levels for ENEA scenario.

Under ENEA scenario weather conditions, for both AUG and NPT varieties, reduction in total plant dry matter, yield and harvest index starts at late transplanting dates moving from 2011 to 2050. Variability among years exists at early transplanting dates having at year 2050 values near to those of 2011. Under MPI, on the other hand, reduction in growth parameters starts even at early transplanting, giving better results for early transplanting than late transplanting. MPI scenario weather conditions will have stronger and sharper effect on plants than ENEA scenario weather conditions.

As recommendations for field-grown processing tomato grower, we can advice them to start growing cycle as early as possible in order to have the maximum possible yield amount by avoiding extreme changes in weather conditions at maturity phase. Farmers should be also

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aware about irrigation frequency and amount as both scenarios expect reduction in precipitation. At breeder level, his future plan should be directed to produce adapted processing tomato varieties to heat resistance, which will be needed in the coming future for the enhancement of processing tomato production.

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## **General Conclusions and Future Prospective**

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Assessing the environmental influences and agronomic practices on field grown processing tomato showed several notes to take into consideration. Conducting open field experiments gave the opportunity to see the complete view about environmental effects on growth and yield of the varieties under study. Mulching the soil under different season weather conditions gave a clear idea about its feasibility for processing tomato production under weather conditions studied.

Under semi-dry season, mulching the soil is a useful tool to decrease plant water consumption levels and to increase yield and water use efficiency at the transplanting dates studied. Under mulched conditions, NPT 63 variety is a recommended variety for processing tomato growers due to its vigour characteristics. With a rainy season, mulching the soil is an added cost without ameliorating yield comparing to non-mulched conditions. Early-spring transplanting is the best time for processing tomato in such region (confirmed finding). NPT 63 variety is a recommended variety under both mulched and non-mulched conditions.

The evaluation of the CSM-CROPGRO-Tomato model following calibration showed a good performance of simulated values when comparing with observed data. The model simulated yield very well for the second, third, and fourth planting dates for all varieties under study. This indicates that under northeastern Italian conditions it would be possible to use the model and to simulate the possible yield of different processing tomato varieties and different seasonal and weather conditions.

In order to evaluate the simulation capability of the model for a larger range of conditions, further work should be done regarding the genotype coefficients for each variety under study. CSM-CROPGRO-Tomato model is not yet designed for mulched conditions and further studies should be done in this regard as well. The model could be used as a decision making tool helping in regional short term plans. Other tomato varieties could be taken into consideration in order to calibrate the model for other environmental and agronomic conditions. CSM-CROPGRO-Tomato is ready to be used under different future environmental scenarios in order to help farmers in taking decision at long term national plans.

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The calibrated CSM-CROPGRO-Tomato model simulates yield and growing cycle length and length of phenology stages using future long term weather datasets for the period from 2011 to 2050. These datasets are obtained by ENEA and MPI downscaling methods, which are predicting future data based on A1B-SRES-IPCC scenario. Plants under MPI scenario weather conditions will be more affected than under ENEA scenario weather conditions. Therefore, changes in total plant dry matter and yield over coming years will be sharper using MPI scenario. Global solar radiation and minimum and maximum temperature will affect growing cycle length. There is a negative correlation between growing cycle to maturity length and values of average temperature. Yield is also affected negatively by season average temperature. As long was the growing cycle as low was temperature average during the growing season.

Under northeastern Italian conditions it is possible to use the model and to simulate the possible yield of different processing tomato varieties and different seasonal and weather conditions. CSM-CROPGRO-Tomato model is considered as a good tool for policymakers in the region under study, which can give us a clear indication about influences of different climatic and agronomic practices. In this way we can put future plans depending on the adaptation options given by the model. Model flexibility comes from the model prosperities which enable us to ask “what if” questions having the output of the model which carry us to take the right decision depending on the findings we have.

Several future climate scenarios of IPCC (i.e. Had3 F1A1 and PCM B1) can be applied to use the CSM-CROPGRO-Tomato model in simulating the potential processing tomato growth and yield at different transplanting dates. This helps the decision makers and farmers in particular, to decide the optimal future plan in the region under study. Further studies can also be extended to other locations with other climate change potentials.

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## **Appendices**

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## Appendix 1: Experimental detail file (FileX) for 2010 experimental datasets as an example for such file

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\*EXP.DETAILS: PDLG1001TM CC TRIAL, 2010 PADOVA, ITALY

\*GENERAL

@PEOPLE

Department of Environmental Agronomy and Crop Production, Padova University

@ADDRESS

Viale dell'Universita, 16

@SITE

AGRIPOLIS

\*TREATMENTS

		-----FACTOR LEVELS-----															
@N	R O C	TNAME	CU	FL	SA	IC	MP	MI	MF	MR	MC	MT	ME	MH	SM		
1	1	1	0	TD1-AUG	M	1	1	0	1	1	2	1	0	0	0	0	1
2	1	1	0	TD1-NPT	M	2	1	0	1	2	2	1	0	0	0	0	1
3	1	1	0	TD2-AUG	M	1	1	0	1	3	4	1	0	0	0	0	1
4	1	1	0	TD2-NPT	M	2	1	0	1	4	4	1	0	0	0	0	1
5	1	1	0	TD3-AUG	M	1	1	0	1	5	6	1	0	0	0	0	1
6	1	1	0	TD3-NPT	M	2	1	0	1	6	6	1	0	0	0	0	1
7	1	1	0	TD4-AUG	M	1	1	0	1	7	8	1	0	0	0	0	1
8	1	1	0	TD4-NPT	M	2	1	0	1	8	8	1	0	0	0	0	1
9	1	1	0	TD1-AUG	NM	1	1	0	1	1	1	2	0	0	0	0	1
10	1	1	0	TD1-NPT	NM	2	1	0	1	2	1	2	0	0	0	0	1
11	1	1	0	TD2-AUG	NM	1	1	0	1	3	3	3	0	0	0	0	1
12	1	1	0	TD2-NPT	NM	2	1	0	1	4	3	3	0	0	0	0	1
13	1	1	0	TD3-AUG	NM	1	1	0	1	5	5	4	0	0	0	0	1
14	1	1	0	TD3-NPT	NM	2	1	0	1	6	5	4	0	0	0	0	1
15	1	1	0	TD4-AUG	NM	1	1	0	1	7	7	5	0	0	0	0	1
16	1	1	0	TD4-NPT	NM	2	1	0	1	8	7	5	0	0	0	0	1

\*CULTIVARS

@C CR INGENO CNAME

1 TM TM0021 AUGUSTO F1

2 TM TM0022 NPT 63

\*FIELDS

@L	ID_FIELD	WSTA	FLSA	FLOB	FLDT	FLDD	FLDS	FLST	SLTX	SLDP	ID_SOIL	FLNAME
1	PDLG1001	PDLG1001	-99	-99	-99	-99	-99	-99	-99	-99	PDLg100001	-99
@L	.....XCRD	.....YCRD	.....ELEV	.....AREA	.SLEN	.FLWR	.SLAS	FLHST	FHDUR			
1	-99	-99	-99	-99	-99	-99	-99	-99	-99			

---

\*SOIL ANALYSIS

@A SADAT SMHB SMPX SMKE SANAME  
1 10103 -99 -99 -99 -99  
@A SABL SADM SAOC SANI SAPHW SAPHB SAPX SAKE SASC  
1 15 -99 -99 -99 -99 -99 -99 -99 -99

\*INITIAL CONDITIONS

@C PCR ICDAT ICRT ICND ICRN ICRE ICWD ICRES ICREN ICREP IC RIP ICRID ICNAME  
1 MZ 10105 -99 -99 1 1 150 -99 .15 -99 100 30 -99  
@C ICBL SH2O SNH4 SNO3  
1 5 .174 1.6 14.4  
1 10 .174 1.6 14.4  
1 15 .174 1.6 14.4

\*PLANTING DETAILS

@P PDATE EDATE PPOP PPOE PLME PLDS PLRS PLRD PLDP PLWT PAGE PENV PLPH SPRL  
PLNAME  
1 10119 -99 8 -99 T R 40 0 10 5.55 38 18.9 1 13  
TD1-AUG  
2 10119 -99 8 -99 T R 40 0 10 10.7 38 18.9 1 15  
TD1-NPT  
3 10137 -99 8 -99 T R 40 0 10 28.4 46 19.6 1 17  
TD2-AUG  
4 10137 -99 8 -99 T R 40 0 10 23.2 46 19.6 1 20  
TD2-NPT  
5 10140 -99 8 -99 T R 40 0 10 12.5 38 21.3 1 13  
TD3-AUG  
6 10140 -99 8 -99 T R 40 0 10 17.9 38 21.3 1 15  
TD3-NPT  
7 10150 -99 8 -99 T R 40 0 10 19 38 22 1 15  
TD4-AUG  
8 10151 -99 8 -99 T R 40 0 10 18.8 38 22 1 17  
TD4-NPT

\*IRRIGATION AND WATER MANAGEMENT

@I EFIR IDEP ITHR IEPT IOFF IAME IAMT IRNAME  
1 1 30 50 100 GS000 IR001 10 TD1 not mulched  
@I IDATE IROP IRVAL

---

---

```

1 10142 IR005 1.6
1 10183 IR005 80.3
1 10193 IR005 80.3
1 10223 IR005 80.3
@I EFIR IDEP ITHR IEPT IOFF IAME IAMT IRNAME
2 1 30 50 100 GS000 IR001 10 TD1 mulched
@I IDATE IROP IRVAL
2 10142 IR005 1.8
2 10183 IR005 4.2
2 10193 IR005 18.4
2 10223 IR005 18.4
@I EFIR IDEP ITHR IEPT IOFF IAME IAMT IRNAME
3 1 30 50 100 GS000 IR001 10 TD2 not mulched
@I IDATE IROP IRVAL
3 10142 IR005 1.9
3 10183 IR005 92.2
3 10193 IR005 65.5
3 10223 IR005 65.5
@I EFIR IDEP ITHR IEPT IOFF IAME IAMT IRNAME
4 1 30 50 100 GS000 IR001 10 TD2 mulched
@I IDATE IROP IRVAL
4 10142 IR005 1.5
4 10183 IR005 1.8
4 10193 IR005 19.4
4 10223 IR005 19.4
@I EFIR IDEP ITHR IEPT IOFF IAME IAMT IRNAME
5 1 30 50 100 GS000 IR001 10 TD3 not mulched
@I IDATE IROP IRVAL
5 10142 IR005 1.7
5 10183 IR005 57.6
5 10193 IR005 38.9
5 10223 IR005 38.9
@I EFIR IDEP ITHR IEPT IOFF IAME IAMT IRNAME
6 1 30 50 100 GS000 IR001 10 TD3 mulched
@I IDATE IROP IRVAL
6 10142 IR005 2.5
6 10183 IR005 2.6
6 10193 IR005 17.3
6 10223 IR005 17.3

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```

@I EFIR IDEP ITHR IEPT IOFF IAME IAMT IRNAME
7 1 30 50 100 GS000 IR001 10 TD4 not mulched

```

```

@I IDATE IROP IRVAL
7 10142 IR005 .2
7 10183 IR005 52.5
7 10193 IR005 51.7
7 10223 IR005 51.7

```

```

@I EFIR IDEP ITHR IEPT IOFF IAME IAMT IRNAME
8 1 30 50 100 GS000 IR001 10 TD4 mulched

```

```

@I IDATE IROP IRVAL
8 10142 IR005 .4
8 10183 IR005 22.3
8 10193 IR005 21
8 10223 IR005 21

```

\*FERTILIZERS (INORGANIC)

```

@F FDATE FMCD FACD FDEP FAMN FAMP FAMK FAMC FAMO FOCD FERNAME
1 10115 FE016 AP002 30 0 0 120 0 0 0 0 Mulched
1 10115 FE005 AP002 30 300 0 0 0 0 0 0 Mulched
1 10118 FE013 AP002 30 0 100 0 0 0 0 0 Mulched
2 10115 FE013 AP002 30 0 100 0 0 0 0 0 TD1 NM
2 10115 FE016 AP002 30 0 0 120 0 0 0 0 TD1 NM
2 10118 FE005 AP002 30 100 0 0 0 0 0 0 TD1 NM
2 10179 FE005 AP002 30 50 0 0 0 0 0 0 TD1 NM
3 10115 FE016 AP002 30 0 0 120 0 0 0 0 TD2 NM
3 10115 FE013 AP002 30 0 100 0 0 0 0 0 TD2 NM
3 10137 FE005 AP002 30 50 0 0 0 0 0 0 TD2 NM
3 10160 FE005 AP002 30 50 0 0 0 0 0 0 TD2 NM
3 10188 FE005 AP002 30 50 0 0 0 0 0 0 TD2 NM
4 10115 FE013 AP002 30 0 100 0 0 0 0 0 TD3 NM
4 10115 FE016 AP002 30 0 0 120 0 0 0 0 TD3 NM
4 10140 FE005 AP002 30 50 0 0 0 0 0 0 TD3 NM
4 10172 FE005 AP002 30 50 0 0 0 0 0 0 TD3 NM
4 10200 FE005 AP002 30 50 0 0 0 0 0 0 TD3 NM
5 10115 FE013 AP002 30 0 100 0 0 0 0 0 TD4 NM
5 10115 FE016 AP002 30 0 0 120 0 0 0 0 TD4 NM
5 10150 FE005 AP002 30 50 0 0 0 0 0 0 TD4 NM
5 10181 FE005 AP002 30 50 0 0 0 0 0 0 TD4 NM
5 10209 FE005 AP002 30 50 0 0 0 0 0 0 TD4 NM

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\*RESIDUES AND ORGANIC FERTILIZER

@R RDATE RCOD RAMT RESN RESP RESK RINP RDEP RMET RENAME  
1 10105 -99 -99 -99 -99 -99 -99 -99 -99 -99

\*CHEMICAL APPLICATIONS

@C CDATE CHCOD CHAMT CHME CHDEP CHT .CHNAME  
1 10105 -99 -99 -99 -99 -99 -99

\*TILLAGE AND ROTATIONS

@T TDATE TIMPL TDEP TNAME  
1 10105 TI022 -99 -99

\*ENVIRONMENT MODIFICATIONS

@E ODATE EDAY ERAD EMAX EMIN ERAIN ECO2 EDEW EWIND ENVNAME  
1 10105 A 0 A 0 A 0 A 0 A 0.0 A 0 A 0 A 0

\*HARVEST DETAILS

@H HDATE HSTG HCOM HSIZE HPC HBPC HNAME  
1 10105 GS000 -99 -99 -99 -99

\*SIMULATION CONTROLS

@N GENERAL NYERS NREPS START SDATE RSEED SNAME..... SMODEL  
1 GE 1 1 S 10105 2150 DEFAULT SIMULATION CONTR  
@N OPTIONS WATER NITRO SYMBI PHOSP POTAS DISES CHEM TILL CO2  
1 OP Y Y N N N N N Y M  
@N METHODS WTHR INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM MESEV MESOL  
1 ME M M E R S L R 1 G S 2  
@N MANAGEMENT PLANT IRRIG FERTI RESID HARVS  
1 MA R R R N M  
@N OUTPUTS FNAME OVVIEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT VBOSE CHOUT OPOUT  
1 OU N Y Y 1 Y Y Y Y Y Y N Y N Y

@ AUTOMATIC MANAGEMENT

@N PLANTING PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN  
1 PL 10001 10001 40 100 30 40 10  
@N IRRIGATION IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF  
1 IR 30 50 100 GS000 IR001 10 1  
@N NITROGEN NMDEP NMTHR NAMNT NCODE NAOFF

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1 NI	30	50	25	FE001	GS000
@N RESIDUES	RIPC	RTIME	RIDEP		
1 RE	100	1	20		
@N HARVEST	HFRST	HLAST	HPCNP	HPCNR	
1 HA	0	01001	100	0	

-

---

## Appendix 2: Soil file (SOIL.SOL) used to calibrate the model for the two pilot sites of 2009 and 2010

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```

*SOILS: General DSSAT Soil Input File
! DSSAT v4.5; 07/01/2008
!
! Standard Soil Profiles
!
! The following generic information was developed by A.J. Gijsman:
!
! - BD was estimated as  $BD = 100 / (SOM\% / 0.224 + (100 - SOM\%) / \text{mineral BD})$ 
!   (Adams, 1973; Rawls and Brakensiek, 1985).
! - LL and DUL are according to Saxton et al., 1986.
! - SAT was taken as a fraction of porosity (Dalglish and Foale, 1998):
!   0.93 for soil classes S, SL and LS; 0.95 for soil classes L, SIL, SI,
!   SCL and SC; and 0.97 for soil classes C, CL, SIC and SICL.
!   For this, porosity was estimated as:  $POR = 1 - BD / APD$  (in which APD
!   is the adjusted particle density, i.e. corrected for SOM; Baumer and Rice, 1988).
! - The ranges of LL and DUL values were calculated by stepping through the
!   complete texture triangle in steps of 1% sand, 1% silt and 1% clay (>5000
!   combinations), but with the texture limitations that Saxton set for his method
!   taken into consideration. For SAT, these limitations do not hold, as this was
!   based on POR and not on Saxton. See Gijsman et al., 2002.
! - The root growth distribution function SRGF was calculated as:
!    $SRGF = 1 * EXP(-0.02 * LAYER\_CENTER)$ ; SRGF was set 1 for LAYER_BOTTOM <= 15.
!
! SOIL CLASS      BD              LL              DUL              SAT
! =====
! C      1.129 - 1.512    0.220 - 0.346    0.330 - 0.467    0.413 - 0.488
! CL     1.243 - 1.502    0.156 - 0.218    0.282 - 0.374    0.417 - 0.512
! L      1.245 - 1.483    0.083 - 0.156    0.222 - 0.312    0.415 - 0.501
! LS     1.353 - 1.629    0.059 - 0.110    0.137 - 0.185    0.355 - 0.416
! S      1.446 - 1.574    0.055 - 0.085    0.123 - 0.158    0.374 - 0.400
! SC     1.501 - 1.593    0.195 - 0.294    0.276 - 0.389    0.376 - 0.409
! SCL    1.475 - 1.636    0.132 - 0.191    0.213 - 0.304    0.360 - 0.418
! SI     0.978 - 1.464    0.096 - 0.099    0.299 - 0.307    0.442 - 0.488
! SIC    1.307 - 1.446    0.224 - 0.326    0.379 - 0.456    0.455 - 0.489
! SICL   1.248 - 1.464    0.155 - 0.219    0.324 - 0.392    0.448 - 0.511
! SIL    0.968 - 1.464    0.082 - 0.152    0.240 - 0.333    0.439 - 0.547
! SL     1.142 - 1.647    0.066 - 0.133    0.164 - 0.243    0.348 - 0.499
!
! =====

```



---

```
! Start of Generic soil profiles
!=====
!
! The 12 Generic soils for SOIL.SOL, as estimated by Arjan Gijssman:
!
! - LL, DUL are according to the Nearest Neighbor method (Jagtap et al, 2004)
! - Ksat at -99
! - BD according to Gijssman et al (2002)
! - SAT based on the APSRU manual (Dalgliesh and Foale, 1998); i.e. 93-97% of porosity
!   depending on the soil type) in which porosity is according to Baumer and Rice (1988).
!
! References
! Adams W.A. 1973. The effect of organic matter on the bulk and true densities of some
!   uncultivated podzolic soils. J. Soil Science 24, 10-17.
! Baumer O.W. and Rice J.W. 1988. Methods to predict soil input data for DRAINMOD.
!   Am. Soc. Agr. Eng. Paper 88-2564
! Dalgliesh, N.P., and M.A. Foale. 1998. Soil Matters - monitoring soil water and nitrogen
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*Pdlg090001  -99      L      180  Agripolis
@SITE        COUNTRY    LAT      LONG SCS FAMILY
Legnaro      Italy      11.58   45.21 Loamy
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
  -99   .13    6    .6    75    1    1  IB001  IB001  IB001
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI  SLHW  SLHB  SCEC  SADC
  0   -99  .099  .25  .419  1    .68  1.61  1.8  18.6  41.3  -99  -99   8   -99  14.8  -99
  10  -99  .099  .25  .419  1    .68  1.61  1.6  18.6  41.3  -99  -99   8   -99  14.8  -99
  40  -99  .099  .25  .419  1    .68  1.61  1.4  18.6  41.3  -99  -99   8   -99  14.8  -99
  80  -99  .162  .336  .504  .301  1.32  1.7    .9  17.4  44.2  -99  -99   8   -99  14.8  -99
  120 -99  .167  .369  .545  .135  .68  1.38   .7  18.4  57.7  -99  -99   8   -99  14.8  -99
  180 -99  .219  .417  .534  .05   .15  1.49   .2  28.7  52.8  -99  -99   8   -99  14.8  -99

*Pdlg100001  -99      L      100  Agripolis
@SITE        COUNTRY    LAT      LONG SCS FAMILY
Legnaro      Italy      11.58   45.21 Loamy
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
  -99   .13    6    .6    75    1    1  IB001  IB001  IB001
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI  SLHW  SLHB  SCEC  SADC
  0   -99  .099  .25  .419  1    .68   .7  1.2  18.6  41.3  -99  -99  8.4  -99  14.8  -99
  20  -99  .099  .25  .419  1    .68   .7  1.1  18.6  41.3  -99  -99  8.3  -99  14.8  -99
  40  -99  .099  .25  .419  1    .68   .8  .9  18.6  41.3  -99  -99  8.3  -99  14.8  -99
  80  -99  .162  .336  .504  .301  1.32   .8  .7  17.4  44.2  -99  -99  8.4  -99  14.8  -99
  100 -99  .167  .369  .545  .135  .68   .8  .2  18.4  57.7  -99  -99  8.4  -99  14.8  -99

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### Appendix 3: Codes of plant growth parameters used in calibration of CSM-CROPGRO-Tomato model

CWAD	Tops weight (kg [dm] ha <sup>-1</sup> )
CWAM	Tops weight at maturity (kg [dm] ha <sup>-1</sup> )
FPWAD	Total fresh fruit weight (kg ha <sup>-1</sup> )
FPWAM	Fresh fruit weight at maturity (kg ha <sup>-1</sup> )
HIPD	Fruit harvest index (fruit top <sup>-1</sup> )
HIPM	Fruit harvest index at maturity
L Aid	Leaf area index
PWAD	Fruit weight (kg [dm] ha <sup>-1</sup> )
PWAM	Fresh fruit weight at maturity (kg ha <sup>-1</sup> )
P#AD	Fruit number (no m <sup>-2</sup> )
P#AM	Fruit number at maturity (no m <sup>-2</sup> )
VWAD	Vegetative weight (stem+leaf) (kg ha <sup>-1</sup> )