Sunflower Modelling: A Review

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Abstract

Vegetable oils are a key component of human dietary need and health worldwide. Oil quality of sunflower is better than all others because of the higher percentage of the linoleic acid that is the most appropriate character missing in all other oilseed crops. Changing climate and extreme weather events are making crop highly vulnerable and threatening global food security. Application of different crop models was evaluated to quantify the sunflower genotypes selection, assessment of phenotypic plasticity, physiology, and estimation of seed yield and oil concentration in response to the climate variability. The present study evaluated the worldwide sunflower modelling performance, and a case study of SUNFLO hybrid modelling technique was assessed for crop model adaptation to new genotypes under contrasting environment. Extended field experiment was conducted at 52 locations (28 genotypes) at the 75% of the total sunflower cultivated region in France. Compared to initial models the experiential correlation decreased mean square error (MSE) on an average of 54% for seed yield production, and 26% for oil content concentration. The study also identified smart management practices and evaluated the performance of different models and concluded with the utilization of hybrid modelling skills. Further research expresses the thrust to use system modelling for screening the existing hybrids on grounds of their responses to several growth parameters and adaptation

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capacity to rapidly changing climatic conditions. This will eventually minimize the yield losses and help in increasing the crop yield even in limited resources. The present study is also proposing a clear optimization framework for genetic diversity of sunflower hybrids and management practices under changing climatic scenario.

Keywords

Climate variability · Crop adaptation · Smart management · Modelling sunflower

11.1 Introduction

Sunflower belongs to the Asteraceae family, formerly denoted as the Compositae. The wild sunflower (diploid annual *Helianthus annuus*) has history back to 0.5 to 1 million years for producing seeds (Rieseberg et al. 1991; Harter et al. 2004), and widely dispersed across many states of the United States, i.e. temperate North America. Currently, wild annual *Helianthus annuus* nurture throughout the United States but habitats are more confined to north of the Trans-Mexican Volcanic Belt (Heiser et al. 1969; Lentz et al. 2008a). Domesticated *Helianthus annuus* are planted throughout Northern America (Lentz et al. 2008a, 2008b). Sunflower (*Helianthus annuus* L.), a famous ornamental plant due to its sun like artistic flower shape (Badouin et al. 2017; Ma et al. 2019), is one of the major oil seed crops in the world (Salunkhe et al. 1992; Putt 1997; Stefansson et al. 2007). Globally, it is planted on 24.77 million hectares with an average yield of 44.31 million metric tons and covers 8% of the world oil seed market (USDA 2016). Pakistan being deficient in edible oil production invests almost 2.71 billion US dollars to import edible oil (Govt. of Pakistan 2017). Sunflower shares 9.19% in local edible oil production followed by cotton and rapeseed/mustard (Govt. of Pakistan 2017; Amin et al. 2017; Nasim et al. 2018).

Edible oils, especially vegetable oils, are a key component of human dietary need and also health (Gholamhoseini et al. 2013; Manivannan et al. 2015). Oil quality of sunflower is better than all others because of the higher percentage of the linoleic acid that is the most appropriate character missing in all other oilseed crops (Nasim et al. 2011). The sunflower oil is also rich in the A, D, E and K vitamins. Sunflower oil is also free from the toxic compounds (Abbas et al. 2017). Sunflower seed comprises of 40–50% oil and 17–20% proteins (Abbas et al. 2017; Amin et al. 2018). This high percentage of edible oil highlighted its potential to minimize the feed gap between production and consumption and ensure food security for future population of the world. Sunflower belongs to tropical and subtropical lands, where semi-arid to arid climate persists. It can be grown in different environmental conditions ranging from humid to dry lands accompanying irrigation. However, like other agri-crops, sunflower productivity is affected by different biotic (pests) and abiotic factors (drought, heat and salinity) (Pekcan et al. 2015; Robert et al. 2016). The optimum growth and development temperature for sunflower plant ranges from 26 to 29 °C (Rondanini et al. 2006; Awais et al. 2017; Hammad et al.

2017). Climate change is a threat to sustainable crop production (Kalyar et al. 2013) and agricultural land is shrinking day by day due to urbanization (Farooq et al. 2012) leading to the competition for water between different users, and plants will suffer from drought (Elliott et al. 2014).

In the past few decades, different areas of the world (Asia and Africa) faced hilarious drought stresses (Miyan 2015; Farooq et al. 2014) which raised the value of climate study. Drought stress mostly affects the crops at early stages of growth (Debaeke et al. 2017) depending on the plant species, like in sunflower; it suppresses the seed germination, stem elongation and leaf expansion (Fulda et al. 2011; Fatemi 2014). Even though domesticated sunflower has potential to adapt climate variations due to its drought escape nature and likely to maintain yield under drought and heat stress conditions, but aforementioned stresses can affect early flowering and achene filling stages due to imbalance in leaf growth and evapotranspiration under deficient soil water (García-López et al. 2014). Leaf wilting under water deficit is the major challenge in semiarid areas due to limited rainfall because ample water at early stage improves vegetative growth (Aboudrare et al. 2006). It is widely reported that drought and heat stresses caused substantial decreases in achene and oil yield as well as affected the oil quality (Soleimanzadeh et al. 2010; Ibrahim et al. 2016). Drought stress is more prune in sunflower at flowering and achene development stage and caused almost 50% yield loss (Kalarani et al. 2004; Hussain et al. 2008) due to pollen infertility resulting empty achene (Lyakh and Totsky 2014; Totsky and Lyakh 2015).

Climate change drives the productivity shift in agriculture, for instance abrupt changes in day and night temperatures severely affect crops production (Ahmed 2020; Farooq et al. 2014). Modern approaches are compulsory to achieve sustainable crop production of current crops to cope the food security challenge (Reddy et al. 2003; Nasim et al. 2016b). According to the Intergovernmental Panel on Climate Change (IPCC), temperature will raise almost 1.4 to 5.8 °C in this century (IPCC et al. 2014; Arshad et al. 2020; Nasim et al. 2016b). Use of modern technologies along with exiting germplasm of sunflower is dire need under limited water supply in the future agriculture. Many researchers tried to observe the impacts of drought and heat stress on oil yield and quality (Gholamhoseini et al. 2013; Manivannan et al. 2015), defined mitigation strategies about drought stress and discovered physiological and molecular responses of crops to stress (Ahmed et al. 2020; Baloğlu et al. 2012; Ghobadi et al. 2013; Bowsher et al. 2016), but no roadmap was developed for sustainable productivity of the sunflower crop.

Use of genetic material from wild and domesticated sunflower is technically possible to improve production of drought-efficient hybrids (Burke et al. 2002). Different population of the sunflower from the world can be used to get valuable genetic resource for further breeding of the sunflower (Van et al. 1997; Burke et al. 2002; Lentz et al. 2008a). Because crop management and genetic improvements (Wang et al. 2016a, b; Awais et al. 2017; Jabran et al. 2017; Nasim et al. 2016a), along with variable phenology of genotypes, are major attributes to cope climate change (Visser and Both 2005; Miller-Rushing et al. 2007; Gordo and Sanz 2010; Szabó et al. 2016). Further research expresses the thrust to use system modelling for screening the existing hybrids on grounds of their responses to several growth parameters and adaptation capacity to rapidly changing climatic conditions (Lentz et al. 2008a). This will eventually minimize the yield losses and help in increasing the crop yield even in limited resources. This review chapter summarizes the potential role of sunflower underutilized crop modelling systems to enhance the efficacy of hybrids system modelling to oilseed security under the changing climate. The present study is also proposing a clear optimization framework for genetic diversity of sunflower hybrids and management practices under future climate scenarios. The objective of the study is to analyse multiple sunflower crop models' skills to simulate the phenotypic variability of composite plant characteristics under ambient climatic conditions, along with observation of several possible modelling approaches to reach high yields.

11.2 Crop Modelling as Agriculture Decision Support Tools

Agriculture science provokes knowledge that allow the researcher to estimate future problems. The world has become complex with several factors threatening the integrity of life from recent years, including increasing pressure of population, scarcity of food, contamination of water, unavailability of land for cultivation of crop and reduction of natural resources. All these factors further effected by climatic condition will lead to changes in the world as we have known it (Wheeler and von Braun 2013). System models component and their interactions are well understood by the scientific studies in the sustainable agroecosystem. Models are considered necessary for understanding agricultural problems. Thus, the overall performance of agroecosystem predicted with the help of models. Agricultural system models play increasingly important roles in the development of sustainable land management across diverse agroecological and socioeconomic conditions because field and farm experiments require large amounts of resources and may still not provide sufficient information in space and time to identify appropriate and effective management practices (Teng and Penning de Vries 1992; Jones et al. 2017).

Models prove helpful for land managers and policy-makers to recognize management option which enhance sustainability of agro-ecosystem (Ahmed and Stockle 2016; Aslam et al. 2017; Ijaz et al. 2017; Jabeen et al. 2017; Wallach et al. 2018; Liu et al. 2019; Asseng et al. 2019; Gyldengren et al. 2020; Schepen et al. 2020; Peng et al. 2020; Stöckle and Kemanian 2020). The soil management and socio-economical and metrological information get across space and time by using these models (Jones et al. 2017). The field study may be carried at potential risk areas. Thus, potential risk area was screened with the help of models. The computer software programmes such as Decision Support Systems (DSSs) make use of other information and model to make site-specific recommendations. These recommendations are helpful in farm financial planning, pest and livestock enterprises management and general crop and land management (Plant 1989; Basso et al. 2013). The evidence-based decision-making is helpful in agriculture to manage environment output. Decision support tools that are software-based may be important to searching for evidence-based decision-making in agriculture. These decisions may be helpful to improve productivity and environmental outputs. The evidence-based decision was improved by using information based upon these tools, and these tools can lead users through clear steps and suggest optimal decision paths. Users design efficient decisions with the help of decision support tools (DSTs). The recommendation of these dynamics' tools was varied according to the inputs from users. These tools may recommend an optimal decision path. Such softer tools facilitate the adviser of farmer for management of farm by recording data and its analysis. Several management techniques and recommendations may be decided based on of the evidence (Ahmed 2011; Ahmed et al. 2012, 2013, 2014, 2016, 2017, 2018, 2019; Ahmad et al. 2017, 2019; Rossi et al. 2014).

Several models are used in agroecosystems such as Environmental Policy Integrated Climate (EPIC) which are considered as cropping model. From a long time, EPIC has been used in a wide range of applications such as irrigation, environmental change, erosion of soil, quality of water and in the crop productivity (Rosenzweig et al. 2014; Wriedt et al. 2009; Elliott et al. 2015). As a combined meteorology and air quality modelling system, WRF/CMAQ is an important decision support tool that is widely used for increasing our understanding of the chemical and physical processes contributing to air quality impairment and for facilitating the development of policies to mitigate harmful effects of air pollution on human health and the environment (Cohan et al. 2007; Compton et al. 2011; Wang et al. 2016a). N deposition to FEST_C EPIC and WRF/CMAQ model provides daily weather inputs, which stimulates growth of plant along with fertilization, planting, harvesting, hydrology and complete biogeochemical properties, under several management practices and soil conditions. In return, information on daily nitrogen fertilization, properties of soil along with the soil moisture, pH or NH_3 conditions stimulated by FEST-C extracts EPIC need input for CMAQ bidirectional NH_3 modelling. The Soil and Water Assessment Tool (SWAT) is important tool that has been used to assess the impact of management of land, soil and weather/climate upon sediments, water and agro-chemical at water shed scale (Abbaspour et al. 2015; Saleh et al. 2000; White et al. 2014).

11.3 Climatic Variability and Smart Practices

Climate Smart Agriculture (CSA) is an approach to help people who manage agricultural systems respond effectively to climate change. The CSA approach pursues the objectives of sustainably increasing productivity and income, adapting to climate change and reducing greenhouse gas emissions whenever possible. CSA is an approach to help smallholder owners implement a variety of smart climate agriculture practices and technologies in order to minimize the negative effects of climate change and variability, but their adoption depends on much of the economic benefits associated with the practices. The goal of CSA practices is to improve the ability of agricultural systems to support food security, sustainably increasing productivity and income, adapting to climate change by incorporating the need for adaptation and mitigation potential into development strategies. However, production Climate Intelligent Farming is a sustainable agricultural production system that addresses climate change. Sustainable agricultural systems offer opportunities for adaptation and mitigation of climate change by contributing to the delivery and maintenance of a wide range of public goods, such as clean water, carbon sequestration, flood protection, recharging groundwater and the value of landscape services. By definition, sustainable agricultural systems are less vulnerable to shocks and stresses. In terms of technologies, productive and sustainable agricultural systems take full advantage of crop varieties and animal breeds and their agroecological and agronomic management (Beddington et al. 2012).

At the field level, there are a wide range of agricultural practices and approaches that are currently available and can contribute to increased production while still focusing on environmental sustainability. Climate change causes some serious challenges to the agricultural sector like temperature increase, heat stress or increased disease which could reduce yields, leading to increased production costs. Appropriate CSA practices are heat tolerant varieties, mulching, water management, shade house, boundary trees. Weeds, Pests and Disease: It is also possible that increases in temperature, moisture and carbon dioxide could result in higher populations of destructive pests so appropriate CSA practices such as intercropping, crop diversity, mulching, container gardening and encased beds should be applied. Irrigation and Rainfall: Changes in climate may also impact the water availability and water needs for agriculture. Rain shortage leads to extended dry spells, and excessive rains lead to erosion and loss of soil fertility, so follow appropriate rainwater harvesting, efficient irrigation, mulching, composting, treated manure and nitrogen fixing trees.

11.4 Uncertainties and Phenotype Optimization: A Case Study

Present global accounting for the annual climatic variability is a recognized issue for projection-based studies of environmental models. Worldwide sunflower is considered as a major oilseed crop. Mainly sunflower seed production considered regions, Europe produces 62% of the total world sunflower production, 19% by the United States and 15% by Asian region (FAO). Improvements in yield with changing environmental conditions depend on the genotype's adaptability to the local climate and cropping systems. It frequently involves intensive field sampling and averaging the simulation outputs over many series of replications. Therefore, researchers need to develop and evaluate the performance of promising sunflower genotypes of every potential variety. Crop modelling can help scientists and breeders in assessment of genotypes, by their capacity to simulate the phenotypic plasticity in response to the climate variability (Fig.11.1). For sunflower, crop physiology has been combined with complementary and different methods in few crop models (Casadebaig et al.

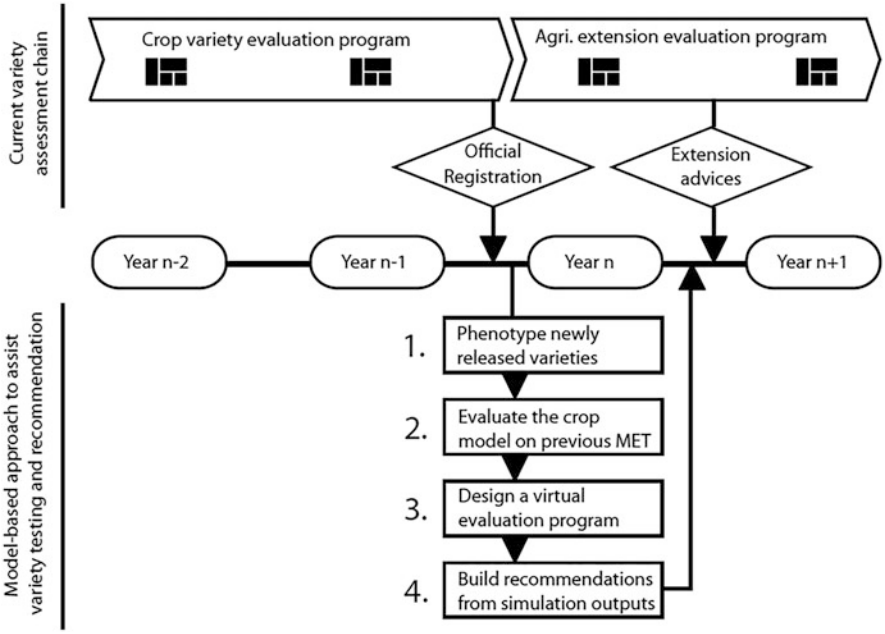

Fig. 11.1 Variety of evaluation processes in crop modelling. (Source: Casadebaig et al. 2016, with permission from Elsevier)

2011). The SUNFLO is a process-based simulation model for sunflower crop that was developed to estimate the grain yield and oil concentration (%) as a function of time, environment (soil and climate), management practices and genetic diversity.

The crop SUNFLO model can simulate variation in promising genotype's performance among different environmental conditions. Model SUNFLO simulates the above-ground biomass production of a sunflower crop from incident solar radiation and mean air temperature. The model works in daily period steps and designates the phenology of plant, leaf area expansion, the biomass production and canopy allocation (Lecoeur et al. 2015). SUNFLO crop model takes into account the behaviour of several genotypes at the same time by the mode of some parameters that are genotype dependent. SUNFLO crop model has the ability to rank the sunflower genotypes with relative performance from its predictive quality. SUNFLO might be helpful to evaluate the capacity ranking of different genotypes due to an appropriate phenotypic variability description. These interactions play important role in yield variability between simulated and actual networks. The originality of the model is that it is SUNFLO tested for estimate differences between genotypes on different criteria (penology, architecture, abiotic stresses). The model also allows forecasting the performance of the oil content of sunflower on the scale and dimensions of a plot and calculates indicators of experienced stresses. Cadic et al. (2012) used the

Table 11.1 Classification characteristic of sunflower crop models to different parameters

Models	Region	Remarks	References
SUNFLO	America Europe Asia	Assessment of genotypes performance Phenotypic plasticity to different environment conditions Simulate grain yield and oil concentration Management practices and field budgeting Abiotic stresses, light interception, fertilizers and water demand	Lecoeur et al. (2015) Cadic et al. (2012) Casadebaig et al. (2011) Lecoeur et al. (2011)
APSIM (APSIM-Sunflower)	Asia Australia	Simulate crop phenology in the intercropping system Under different saline soil conditions to water-extraction coefficient (KL) Root growth pattern in soil profile (XF) N-levels to leaf area (LAI), dry matter (DM) and seed yield (SY) Different sowing (SD) dates and irrigation	Holzworth et al. (2014)
WOFOST (WOFOST-ES)	Asia	Simulate and calibrate environmental stresses factors to estimate best management practices	Zhu et al. (2018)
DSSAT (OILCROP-SUN)	Asia South America	Simulate different hybrids crop growth and development Water and nitrogen limited demands to yield variability Different sowing dates, fertilizer levels and yield potential	Ahmad et al. (2017) Awais et al. (2017) Leite et al. (2014)
SWB	Africa	Simulate the soil water balance and crop growth and development Irrigation scheduling and WUE	
EPIC and ALMANAC	America	Crop phenology, growth, and yield Growth degree days (GDD) and radiation use efficiency (RUE) Combine high yield potential with great adaptability by different management schemes	Kiniry et al. (1992)

SUNFLO crop model for estimation of drought stress index in each environment condition through the response of previously characterized probe genotypes. Furthermore, approach by Picheny et al. (2015) achieves good performances even with limited computational budgets, outclassing significantly more simple practices. In another study, SUNFLO model was developed to simulate the oil concentration and achene yield of sunflower crop with a distinct attention paid to the report of varietal range. The results of Lecoeur et al.'s (2015) SUNFLO biophysical model account for 80 to 90% accuracy of observed variability in different genotype's yield potential. The model is also an interesting tool for investigating the phenotypic variability of complex plant characteristics, i.e. drought, water demand and light interception efficiency. SUNFLO model showed multiple approaches that in several ways are possible to reach high yields (Table 11.1).

The SUNFLO model has 10 genotype-dependent parameters: 2 parameters for growth degree days (GDD) to important development stages, 4 for shoot architecture, 2 for response to water deficit and 2 for biomass allocation in plant. A case study of SUNFLO hybrid modelling technique was evaluated for crop model adaptation to new genotypes. To train the liner model applied in calibration method an extended field experiment was conducted at 52 locations (28 genotypes) at the 75% of the total sunflower cultivated region in France in 2009/10. A total 82 number of trials were conducted and observed over the complete model calibration. The data set of Casadebaig et al. (2016) was reused to validate the model performance. The two major output variables (grain yield, oil concentration) of the simulation were calibrated. Compared to initial models the experiential correlation decreased mean square error (MSE) on an average of 54% for yield production and 26% for oil content. This modelling approach combines the recompenses of phenotyping (genotype-specific) parameters that have a clear meaning and are equal between different genotypes. The benefit of fitting model to the observation data from field, specifically that the modified model, is adapted to a changing environmental condition.

Models often cover a maximum number of crop parameters, perhaps more than one hundred. Some parameters are presumed to apply very commonly and so are not meant to be changed for different applications. For example, in the SUNFLO model (Casadebaig et al. 2011; Lecoeur et al. 2011), there are parameters representing the effect of soil moisture and temperature on rate of nitrogen (N) mineralization. Additional set of parameters is specific to a particular species, which applies to generic models like DSSAT (Jones et al. 2003; Hoogenboom et al. 2012), Agricultural Production System Simulator (APSIM; Holzworth et al. 2014) or (STICS; Jones and Kiniry 1986; Jones 1993; Ritchie and Otter 1984) which can simulate for various species. The SUNFLO model has 10 genotype-dependent parameters (two for degree days to key development stages, four for shoot architecture, two for response to water deficit and two for biomass allocation).

11.5 Sunflower Modelling Way Forward

Development and applications of crop growth models is an effective tool for sustainable agricultural planning and decision-making process. Outdated experimental approaches are overpriced, time-consuming and not resourceful to adopt with changing climatic condition. Modelling of sunflower (*Helianthus annuus* L.) is stimulating because the crop species combines high harvest potential with excessive adaptability. Crop modelling might be an advantageous tool for identifying appropriate and economical management practices for sunflower, particularly climate change vulnerable regions worldwide. The key sunflower crop models are reviewed

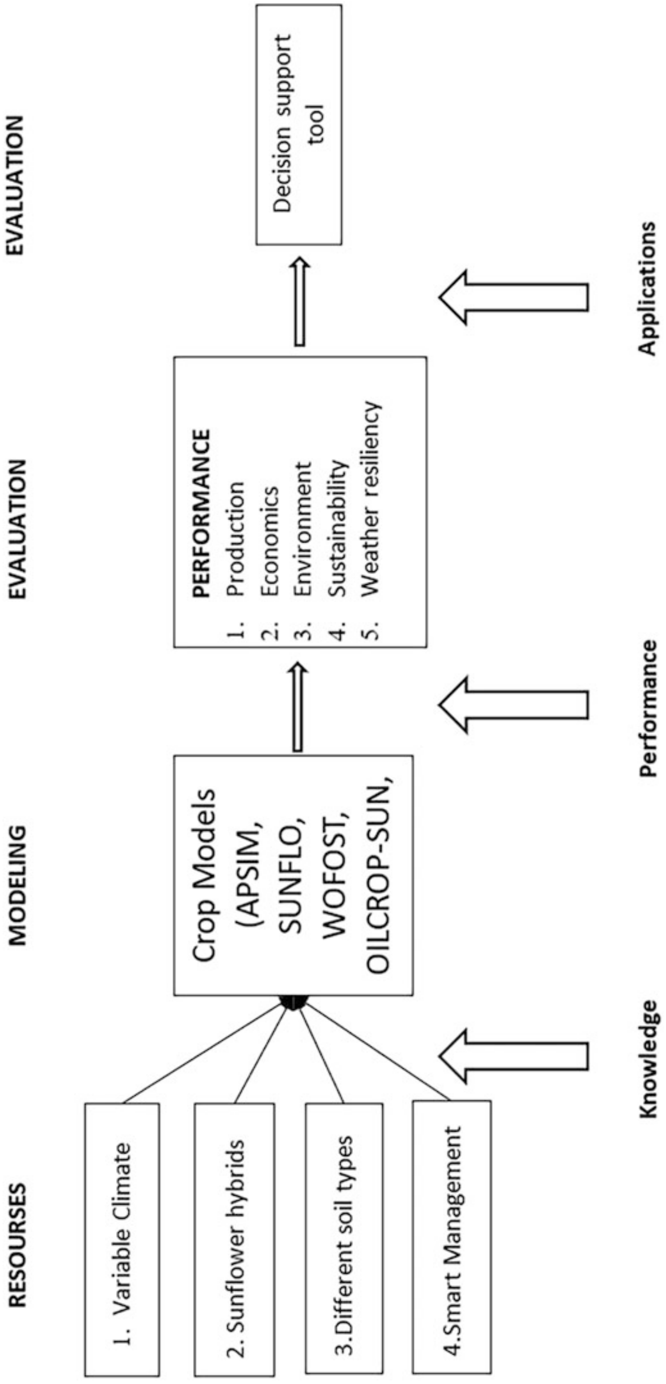

Fig. 11.2 Application of different sunflower models

in this section, with an emphasis on their capability to contribute to smart sunflower crop management (Fig. 11.2).

Numerous research experimentations proved that the modelling skills are effective to evaluate the applicability of the sunflower model within the APSIM to observe the climatic adaptation and resilience by shifting the sowing windows or other parameters (Table 11.1). Zheng et al. tested the APSIM sunflower model on different salinity levels and nitrogen application rates and studied the characteristics including the seed yield (SY), dry matter (DM), and leaf area index (LAI) by modifying the crop lower limit (CLL), the water-extraction coefficient (KL) and the pattern of root exploration in the soil profile (XF). APSIM-SUNFLO modelling tool help researchers to precisely simulate the crop phenology in the intercropping system to signify for the valuation and optimization of intercropping production systems. Based on APSIM-Sunflower model, interaction analysis of irrigation, sowing date and nitrogen application on oil yield of sunflower was simulated, calibrated and validated.

Agricultural monitoring and evaluation of crop plants to environmental stress is vital for the sustainable development of agriculture and food security. Zhu et al. (2018) tested World Food Studies (WOFOST) crop model, WOFOST-ES, which was developed by the addition of a general environmental stress factor (ES) for sunflower simulation to calibrate and validate with observational data to estimate the best managing practices for future (Table 11.1). In another study Leite et al. (2014) evaluated the performance of the crop model OILCROP-SUN to simulate growth and development of sunflower under Brazilian conditions and to discover sunflower water nitrogen-limited, water-limited and potential yield and yield variability over an arrangement of sowing dates. The Soil Water Balance (SWB) was used by Jovanovic and Annandale to simulate the soil water balance and growth of sunflower crop. The detailed meteorological, soil and irrigation data were analysed to calibrate and validate the subroutines of the model. SWB simulations of crop growth and soil water deficit presented the field capacity were inside, or marginally outside the reliability criteria imposed during the modelling.

Meanwhile, other studies showed that the combination of EPIC and ALMANAC models gave realistic yield simulations over changing environment and management possibilities (Kiniry et al. 1992). The application of sunflower models should be valuable both for evaluating the impacts of extreme climate to different management systems and for identifying focus zones where additional basic research is needed. Besides, the drought and limited supplies of water in many countries of the world have increased attention to favourable system modelling approaches in farm management such as efficient irrigation and climate resilient planting system. Furthermore, AquaCrop model has also been successfully applied to estimate the sunflower crop productivity under irrigated and rainfed agricultural conditions to enhance the water use efficiency of the crop plants.

For evaluation of adaptive sunflower hybrids, the SUNFLO model might be supportive to advance genotypic estimation. It will also assist scientists in identification, quantification and modelling of phenotypic changeability of sunflower performance in response to field stresses (abiotic) conditions (Fig. 11.3)

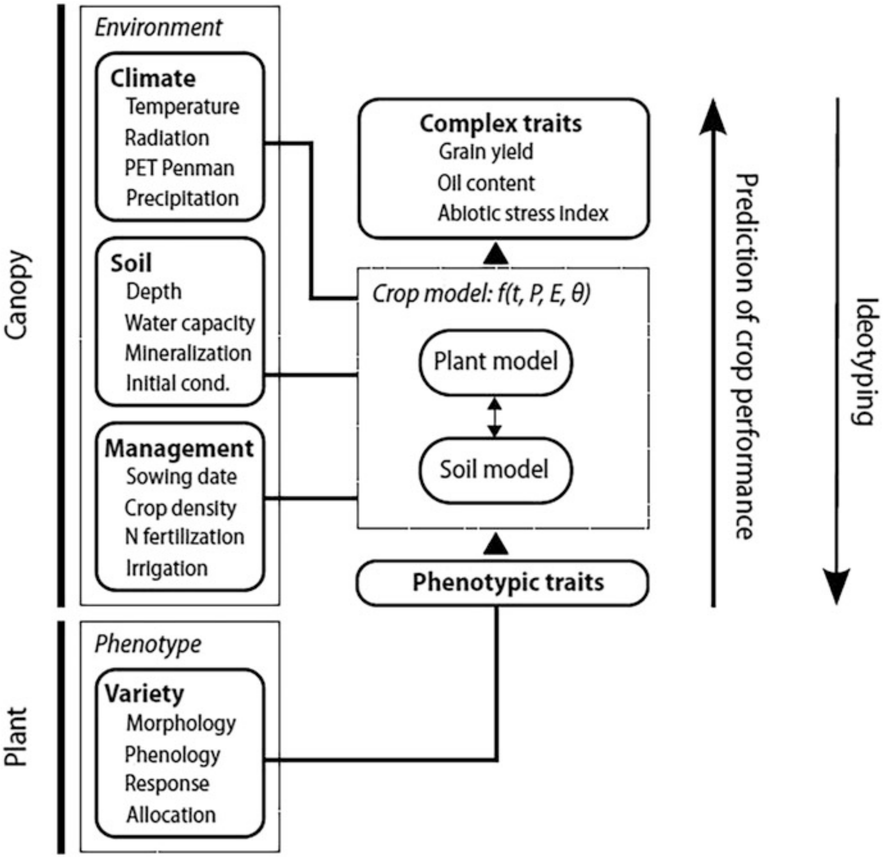

Fig. 11.3 SUNFLO crop model. (Source: Casadebaig et al. 2016, with permission from Elsevier)

(Casadebaig et al. 2016). Furthermore, SUNFLO crop model appears adequately more robust in evaluation of breeding traits which influence on yield to discover innovative practices while diagnosing environmental challenges, respectively (Fig.11.4).

11.6 Summary

In a situation of global climatic change, improving yield under different environmental uncertainties is a major challenge for crop production and food security. The present study proposes various hybrid approaches from adapting a crop model to promising genotypes. This will also combine phenotyping estimation of genotype-dependent parameters with calibration using field data. Review research also suggested that the genotype-dependent constraints of the crop model could be obtained by phenotype or gene-based modelling. Then field data, especially variety trials, could be used to provide a simple empirical correction to the model. The

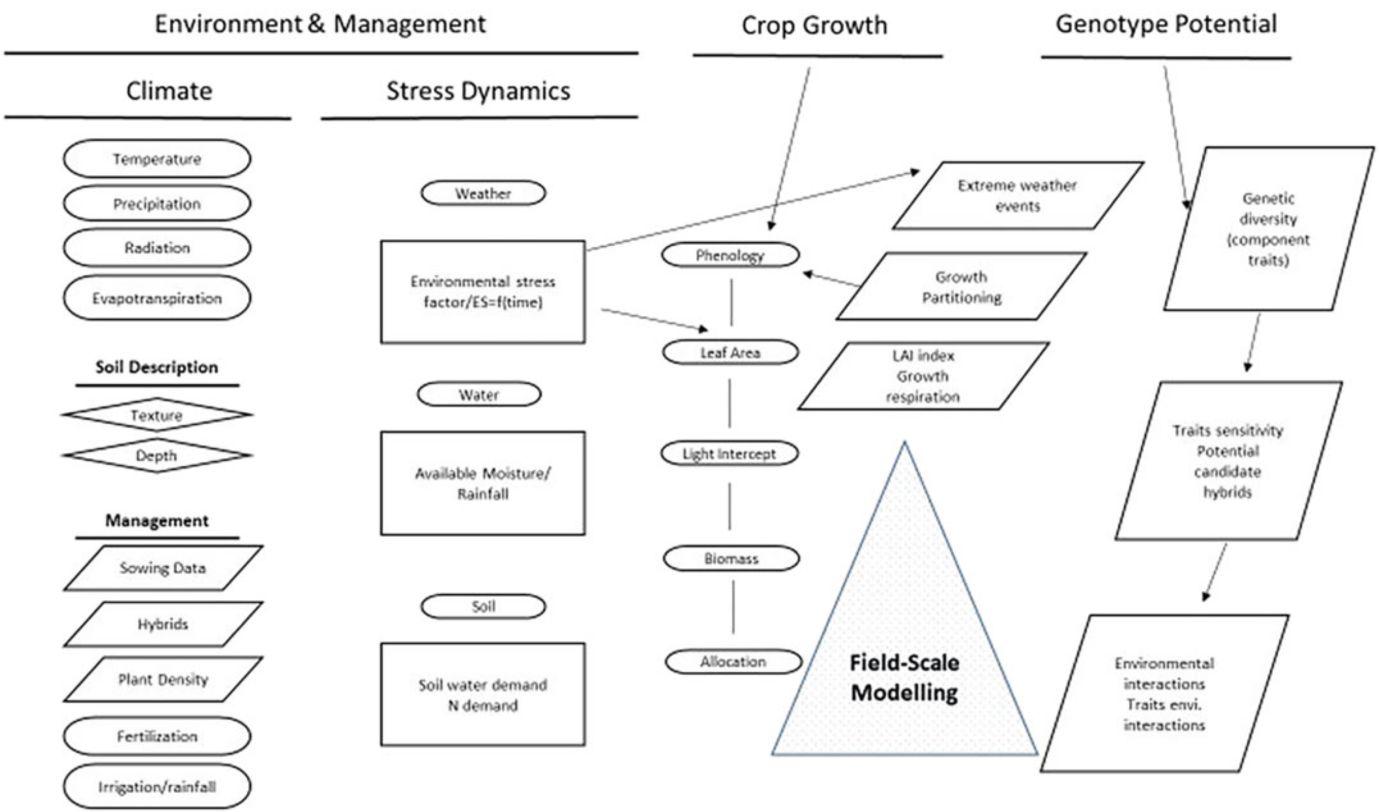

Fig. 11.4 Flow diagram of sunflower crop model

combination the different modelling approach achieves might provide good performances even for limited research budgets, outperforming suggestively more simple strategies. The present study is also proposing a clear optimization framework for genetic diversity of sunflower hybrids and management practices under changing climatic scenario.

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