International Journal of Intelligent Information Systems
2021; 10(6): 117-124
http://www.sciencepublishinggroup.com/j/ijiis
doi: 10.11648/j.ijiis.20211006.13
ISSN: 2328-7675 (Print); ISSN: 2328-7683 (Online)

Review on Decision Support System for Agrotechnology Transfer (DSSAT) Model

Desta Abayechaw

Ethiopia Institute of Agricultural Research, Wondo Genet Agricultural Research Center, Hawassa, Ethiopia

Email address:
destab09@gmail.com

To cite this article:
Desta Abayechaw. Review on Decision Support System for Agrotechnology Transfer (DSSAT) Model. *International Journal of Intelligent Information Systems*. Vol. 10, No. 6, 2021, pp. 117-124. doi: 10.11648/j.ijiis.20211006.13

Received: October 21, 2021; **Accepted**: November 17, 2021; **Published**: November 24, 2021

Abstract: Traditional agronomic experiments were conducted at a specific location in time and space, resulting in long, seasonal, time-consuming, and expensive experiments. An international team of scientists has developed a decision support system for the transfer of agrotechnology, which has been used by researchers from around and the world for 15 years. This package incorporates models for over 42 crops (since Version 4.7.5) as well as tools to facilitate effective use of the models. Tools include database management programs for soil, weather, crop management, and experimental data, utilities, and implementation programs. Crop simulation models simulate growth, development, and yield in accordance with soil-plant-atmosphere dynamics. Over the last few years, it has become increasingly difficult to maintain the DSSAT crop models, partly due to the fact that there were different sets of computer code for different crops with little attention to software design at the level of crop models themselves. Thus, the DSSAT crop models have been re-designed and programmed to facilitate more efficient incorporation of new scientific advances, applications, documentation, and maintenance. The basis for the new DSSAT cropping system model (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. In this review paper, I described the approaches used to model the primary scientific components (soil, crop, weather, and management). Besides, the review paper describes the limitations, the future of the DSSAT model, and its importance. The benefits of the new, re-designed DSSAT–CSM will provide considerable opportunities for its development and others in the scientific community for greater cooperation in interdisciplinary research and in the application of knowledge to solve problems in the field, farm, and higher levels.

Keywords: Agronomy, DSSAT Model, Software Program

1. Introduction

Agricultural decision-makers at all levels need an increasing amount of information to better understand the possible outcomes of their decisions to help them develop plans and policies that meet their goals. An international team of scientists has developed a decision support system for the transfer of agrotechnology (DSSAT) to estimate production, resource use, and risks associated with different crop production practices. The DSSAT is a microcomputer software package that contains crop-soil simulation models, databases for the weather, soil, and crops, and strategy evaluation programs integrated with a 'shell' program which is the main user interface [17]. Furthermore, the Decision Support System for Agrotechnology Transfer (DSSAT) is a set of computer programs for simulating agricultural crop growth [16]. It has been used in many countries by agronomists for evaluating farming methods [35, 2]. One application has been assessing the possible impacts on agriculture of climate change and testing adaptation methods. DSSAT is built with a modular approach, with different options available to represent such processes as evapotranspiration and soil organic matter accumulation, which facilitates testing different representations of processes important in crop growth [8, 22, 26].

DSSAT grew out of the International Benchmark Sites Network for Agrotechnological Transfer (IBSNAT) in the 1980s, with the first official release in 1989 [26]. Version 4, released in 2003, introduced a more modular structure and added tools for agricultural economic analysis and risk assessment [16]. The development has continued in affiliation with the International Consortium for Agricultural Systems Applications (ICASA) [42]. The functionality of DSSAT has also been extended through interfaces with other software such as GIS [35, 34]. DSSAT typically requires input parameters related to soil condition, weather, and management practices such as fertilizer use, irrigation, and characteristics of the crop variety being grown [43]. Many common crops have their characteristics already implemented as DSSAT modules [16].

DSSAT has been in use by more than 16,500 researchers, educators, consultants, extension agents, growers, and policy and decision-makers in over 174 countries worldwide [2019]. The crop models require daily weather data, soil, surface and profile information, and detailed crop management as input. Crop genetic information is defined in a crop species file that is provided with DSSAT and cultivar or variety information that should be provided by the user. Simulations are initiated either at planting or before planting through the simulation of a bare fallow period. These simulations are conducted at a daily step or in some cases, at an hourly time step depending on the process and the crop model. At the end of each day, the plant and soil water, nitrogen, phosphorus, and carbon balances are updated, as well as the crop's vegetative and reproductive development stage [16].

The DSSAT helps decision-makers by reducing the time and human resources required for analyzing complex alternative decisions [37]. It also provides a framework for scientific cooperation through research to integrate new knowledge and apply it to research questions. Before proceeding, some explanation of the use of the term decision support system is needed. Decision support systems (DSS) are interactive computer-based systems that help decision-makers utilize data and models to solve unstructured problems. The current DSSAT ecosystem includes at least one real-world experiment per crop that was used either for model development, calibration, or evaluation. Most researchers have their standard methodology for recording experimental data in field books, spreadsheets, and other electronic media. These individual differences make it somewhat challenging to convert the measured data into a format that can be directly applied in a crop modeling system. DSSAT provides specific tools for entering weather, soil, crop management, and observational data and the systems improve the performance of decision-makers while reducing the time and human resources required for analyzing complex decisions. Therefore, this review aimed to understand the concept, importance, limitation, and future application of the decision support system for the agrotechnology transfer model in new generation agricultural research.

2. The Review of DSSAT Model

2.1. The Concept of DSSAT Model

Traditionally, research for agricultural development and improvement is based on small plot experiments that are conducted for multiple years on a research station and, on occasion, in multiple locations. The outcomes of these experiments are then transmitted in the form of recommendations to farmers through statewide and county-based extension services. Although this approach works well for the United States and Europe, where farms are normally well managed concerning fertilizer, irrigation inputs, and pests and diseases, in some countries funding and resource challenges make this approach less practical [18]. In the early 1980s, the United States Agency for International Development (USAID) made a bold step to support a project that was based on systems analysis of agricultural production to address food security in developing countries. This project for improving agricultural production called the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) scheme was launched in 1992, as an investigation methodology to study the assumption that modeling systems play an important role in agricultural improvement [35].

The international team of scientists working for IBSNAT, developed computer software with a suite of models named Decision Support System for Agrotechnology Transfer (DSSAT) to simulate yield, resource use, and risks related to different crop production practices [36, 12]. The system which consists of files, data formats, computer codes, and user-interface was used for the crop model integration to DSSAT. The models simulate plant growth, development, and yield as a function of plant genetics, weather, soil conditions, and crop management practices [3]. The range of crops simulated is wide: cereals (maize, wheat, rice, sorghum) legumes (peanut, soybean, beans) pasture grass, roots, and tubers (cassava, potatoes). The cereal simulation modules derive from CERES (Crop-Environment-Resource-Synthesis) modeling activities carried out mainly in the 1980s. The CERES-maize module was developed by [15]; the CERES wheat by [29], and CERES rice by [32] among others. The legume module is derived from CROPGRO with components such as PNUTGRO, SOYGRO, BEANGRO among others [4].

The DSSAT has gone through considerable improvement over time, DSSAT was first released (v2.1) in [19]; additional releases were made in 1994 (v3.0) [36] and 1998 (v3.5) [12], 4.0, 4.5, 4.6 and the original design and concept are still viable in the most current version of DSSAT Version 4.7.5 [11] and a proposed future implementation in DSSAT [28]. Crop growth models integrate the effects of soils, weather, management, genetics, and pests on daily growth, and can be used to gain insight into spatial yield variability. Among the numerous crop growth models, the most widely used are the Decision Support for Agrotechnology Transfer (DSSAT) models, which were designed to stimulate growth, development, and yield of a crop growing on a uniform area of land, as well as the changes in soil water, carbon, and nitrogen that take place under the cropping system over time [16]. DSSAT has been in use for the past 15 years by researchers all over the world, for a variety of purposes, including crop management [7] climate change impact studies [1], sustainability research Quemada and Cabrera (1995) and precision agriculture [24], and is well validated for several regions and crops. Included in the DSSAT family are modules that simulate the growth of 16 different crops, including maize, soybeans, wheat, rice, and others.

2.2. Agronomy and DSSAT Model

According to [16] the information needs for agricultural decision-making at all levels are increasing rapidly due to increased demands for agricultural products and increased pressures on land, water, and other natural resources. The generation of new data through traditional agronomic research methods and its publication is not sufficient to meet these increasing needs. Traditional agronomic experiments are conducted at points in time and space, making results site- and season-specific, time-consuming, and expensive. Unless new data and research findings are put into formats that are relevant and easily accessible, they may not be used effectively. The decision support system for agrotechnology transfer (DSSAT) model was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project [13, 37, 39, 17] to facilitate the application of crop models in a system approach to agronomic research. Its initial development was motivated by a need to integrate knowledge about soil, climate, crops, and management for making better decisions about transferring production technology from one location to others where the soils and climate differed [13, 39].

2.3. Importance of DSSAT Model

The DSSAT crop models have been widely used over the last 15 years by many researchers for many different applications. Many of these applications have been made to study management options at study sites, including fertilizer, irrigation, pest management, and site-specific farming. These applications have been conducted by agricultural researchers from different disciplines, frequently working in teams to integrate cropping systems analysis using models with field agronomic research and socioeconomic information to answer complex questions about production, economics, and the environment. [16].

Researchers from all continents have used these models in studying the potential impacts of climate change on agricultural production [31]. The models have also been widely used in studying the potential use of climate forecasts for improving the management of different cropping systems, and the value and risks associated with the use of this information. In addition to research applications, the DSSAT and its crop models have been used in teaching, both in continuing education courses and informal university courses at the graduate and undergraduate levels [37]. There also have been attempts to use these models in advising farmers (through extension services and the private sector). In one application, described by [41] an agricultural company has implemented versions of three of the DSSAT v3.5 models in a comprehensive farmer support software package that is being used by private consultants.

2.4. The DSSAT Ecosystem

The combination of different models, tools, utilities, and applications requires the development of a unique interface that provides easy access for a user who may not be familiar with crop models in general, especially with the challenges of formatting input and output files. Jim Jones conceptualized the design of DSSAT to be an integrated crop modeling platform [17]. DSSAT provides tools to assist a user to prepare the different input files that are needed for running a model, to define the experiments and treatments or scenarios a user wants to simulate, and to conduct an analysis of crop model outputs from the simulations, including a comparison with observed data for model evaluation and strategic analyses for model scenarios (Figure below). To facilitate the interaction between the crop models, the data tools, the utilities, and the application programs, a very strict protocol is required for the file naming convention, specific file formats, and system settings that define the location and names of the model input and output files. This approach was first presented to DSSAT users in DSSAT Version 2.1 [14] and DSSAT Version 3.0 [13] at the end of the IBSNAT Project. The original design and concept are still viable in the most current version of DSSAT Version 4.7.5 [11] and a proposed future implementation in DSSAT [28].

Over time, both the file formats and the file naming conventions have changed, but the approach is still the same. The same flat ASCII file structures are used to provide ultimate portability, something learned after using early proprietary database software that was no longer supported. As a result, a user can easily simulate crop growth, development, and yield for different crops in the same field while making only minor changes to the input files that are crop-specific, such as variety selection, planting date, or plant density. The strict protocol also has allowed programmers to develop new tools and utilities that can be easily incorporated into DSSAT based on standard input and output formats. Examples include the graphics program Easy Grapher [44] the genetic-specific parameter optimizer GLUE [9], and a platform-independent DSSAT shell [28]. The only challenge has been the use of two digits to represent a year, which will be resolved in the next release of DSSAT with the introduction of ICASA Version 2.0 file formats that were defined several years ago [42].

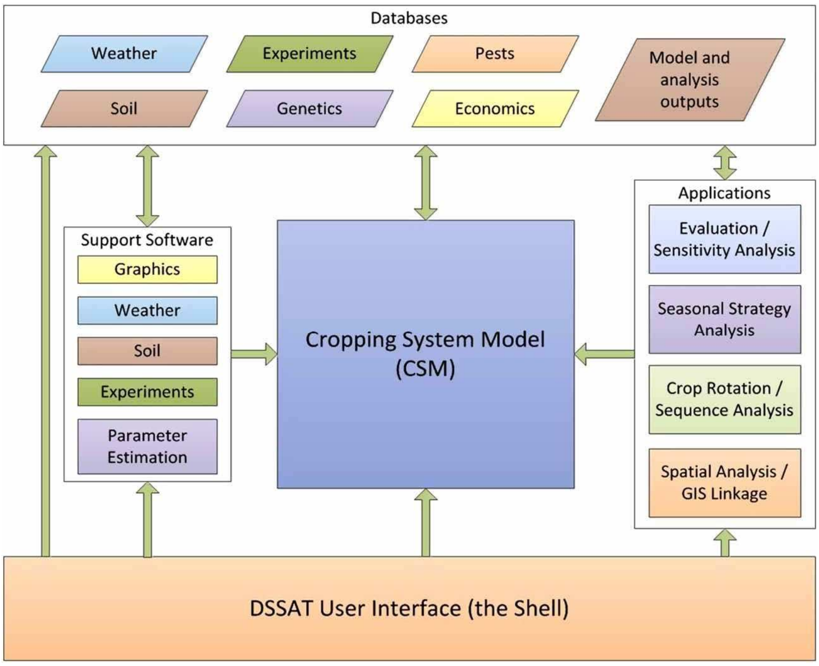

Figure 1. *The DSSAT crop modeling ecosystem.*

2.5. Components for Application of DSSAT Model

The DSSAT is a collection of independent programs that operate together; crop simulation models are at its center [16]. Databases describe the weather, soil, experiment conditions and measurements, and genotype information for applying the models to different situations. The 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 [39, 17]. Besides, programs contained in DSSAT allow users to simulate options for crop management over several years to assess the risks associated with each option. DSSAT was first released (v2.1) in 1989; additional releases were made in 1994 (v3.0) [36] and 1998 (v3.5) [12]. The DSSAT is currently undergoing major revisions, not in its aim but its design. One major reason for this re-design is that each crop model in DSSAT v3.5 had its soil model components. Although simulation of crop rotations was possible in that version, the problems regarding programming, compatibility of soil models, and potential bugs in different sets of code. At the heart of the DSSAT revisions is a new cropping system model (DSSAT/CSM), which incorporates all crops as modules using a single soil model [16].

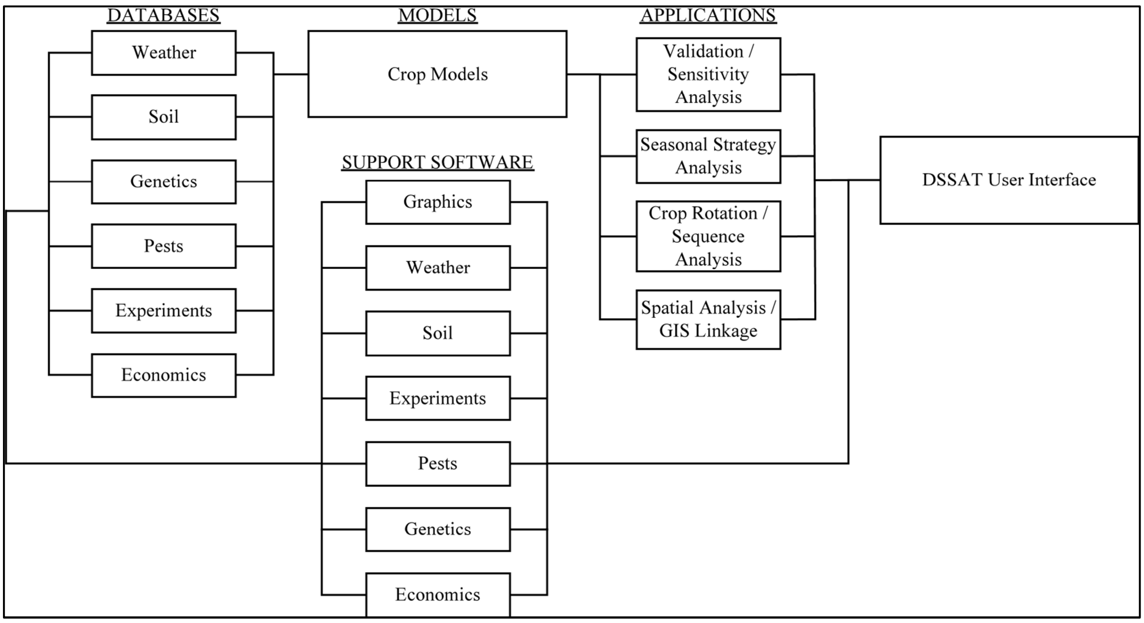

Figure 2. *Diagram of database, application, and support software components and their use with crop models for applications in DSSAT v3.5: Source [16].*

2.6. Re-design of DSSAT Model

The applications provide a broad overview of the many studies that have used the DSSAT and its crop models. These were conducted before the new modular DSSAT/ CSM was developed. Thus, many of these applications have focused on single crops instead of cropping systems. Since the DSSAT/CSM simulates crop and soil processes the same as DSSAT v3.5 (except for the new CENTURY-based soil C and N module), the current version has the same scientific capabilities that were used in most of these previous studies. However, the new DSSAT/ CSM opens the way for more effective research on cropping systems [8] and it opens the way for more effective scientific improvements than ever before due to overcoming many hurdles imposed by the structure of previous versions.

In many past studies, researchers accepted the crop and soil models in DSSAT as they were, but many studies showed that improvements were needed in various parts of the models. In some cases, researchers modified the code to create their versions of crop models, but such efforts were complicated by the design of the models themselves and by the lack of adequate documentation in some cases. The re-design of the DSSAT/CSM was undertaken to help overcome some of these problems as well as to facilitate an efficient evolution for broader and more advanced applications in the future. Although the DSSAT/CSM is new, researchers are already adding new modules for pest dynamics (J. Koo, personal communication), models for new crops (O. Daza, personal communication) [5, 41].

2.7. Limitation of DSSAT Model

The main limitations of DSSAT relate to the included crop models [17]. Models for only a few crops are included in the system and the models do not respond to all environmental and management factors. Missing are the components to predict the effects of tillage, pests, intercropping, excess soil, water, and other factors on crop performance. These models are most useful in regions of the world where weather, water, and nitrogen are the factors that affect crop performance. Their date value has been for demonstrating the potential and in teaching [17]. The performance of these models may not be good under severe environmental stress. The models currently simulate the potential, and water and nitrogen-limited productions, but do not consider many factors that determine yield limitations in many agricultural fields, for example, Phosphorus availability. The soil, water balance model is limited to well-drained soils. [30] recommended the need for a better simulation of the water balance in very poorly drained conditions where oxygen stress will affect crop growth.

One weakness of the DSSAT ecosystem and many other crop modeling systems is the limited capability for handling the impact of biotic stresses caused by insect pests, diseases, and weeds. DSSAT currently has a static system that allows a user to define biotic stressors based on field damage observations. However, there is no coupling with dynamic pest and disease models.

2.8. The Future of DASST Model

One of the challenges of maintaining and developing scientific software platforms in agriculture is the limited availability of resources for software developers. Most grant agencies, both domestic and international, are not as interested in advancing scientific models as in applications. Also, many agricultural scientists are not good programmers, especially in computer languages such as Fortran, Delphi, and Visual Basic that are currently used in DSSAT. Since the start of the development of DSSAT and the crop models, the emphasis has been on scientists developing the crop models, rather than relying on professional programmers who develop the code based on input provided by the scientists. However, this development model is not sustainable, especially when financial resources are limited. Therefore, collaboration is required among programmers who can code in scientifically sound code, and scientists with state-of-the-art expertise. With the migration to Open Source and the sharing of the source code, the DSSAT Development group hopes to expand the community of those interested in advancing and improving the DSSAT ecosystem, including the models as well as the tools and utility programs. The DSSAT Development Sprints are part of this collaboration and so far, the sprints have resulted in crop model improvement for irrigation management [21] a new tool for soil data retrieval from the internet [20] and a new modeling engine for different operating systems [28].

One of the most challenging aspects of the DSSAT crop models is the GSPs, which, for all models, must be estimated for local cultivars and hybrids before any real-world application. There have been efforts to bridge the gap between biotechnology, genetics, plant breeding, and crop modeling using either genes or quantitative trait loci (QTLs). The first, simple, gene-based model, GENEGRO, was developed by [10] more than 20 years ago, linking several genes to the GSPs of the dry bean model, BEANGRO. Predictions for phenology were as accurate as of the original model, while final yield and biomass predictions were more challenging. A similar gene-based approach was applied for soybean by [23]. More recent developments are based on QTLs that are directly or indirectly linked to GSPs or plant traits [40]. As the cost of mapping QTLs/genes becomes cheaper, it is expected that rapid advances can be made in this area. A future model would have QTLs/genes linked to one or more growth and development processes via modules that would allow for the input of gene maps directly into crop models [10]. If successful, this improvement would then reduce the requirements for calibration of a new cultivar for local conditions, assuming that QTL knowledge is public and proper phenotyping of QTL actions has been done [33].

Because DSSAT is a comprehensive software program, it requires the training of agricultural scientists who traditionally specialize in single disciplines and who may not be very familiar with the systems approach that encompasses multiple disciplines. Ideal capacity building requires multiple workshops, starting with the basics of crop modeling and data requirements, followed by data collection for model evaluation, and finishing with model applications, the most critical part of crop modeling and decision support by [19] will be mandatory.

3. Conclusions and Recommendation

The current agricultural production system is challenged with the weather and climate extremes and variability and economic risks. There is pressure to cultivate more healthy food using sustainable practices. At the same time, technology is rapidly improving with new sensor technologies, the internet of things, edge computing, and remote sensing. The amount of data that are being collected for the agricultural production system is exponentially expanding, providing opportunities for data analytics for strategic and actionable decisions. The DSSAT model can play a major role in helping to understand the interaction between Genotype, Environment, and Management (G * E * M) and to provide alternative management options that increase crop yield and quality, optimize resource use, and minimize environmental impact for long term sustainable agricultural production.

In many previous studies, researchers have accepted the crop and soil models in DSSAT as they were, but many studies have shown that improvements were needed in various parts of the models. In some cases, researchers modified the code to create their versions of crop models, but such efforts were complicated by the design of the models themselves and by the lack of adequate documentation in some cases. The re-design of the DSSAT/CSM was undertaken to help overcome some of these problems as well as to facilitate an efficient evolution for broader and more advanced applications in the future. Therefore, Because DSSAT is a comprehensive software program, it requires the training of agricultural scientists more for developing countries like Ethiopia, who traditionally specialize in single disciplines and who may not be very familiar with the systems approach that encompasses the multiple disciplines and it should be recommendable for researchers to use modeling especially DSSAT model in the future agricultural research to plant crops in the computer rather than in the field.

Acknowledgements

The author would like to thanks the instructor Dr. Abera Habte for his advice and guidance in the entire scientific paper writing.

Competing Interests

The authors declare that they have no competing interests.

References

[1] Alexandrov, V. A., and Hoogenboom, G., (2001). The impact of climate variability and change on crop yield in Bulgaria. Agric. Forest Meteorol. 104, 315–327.

[2] Baselala, E. (2012). "Agrotech". Fiji Times. Archived from the original on February 1, 2014. Retrieved January 23, 2014.

[3] Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W.,... & Smith, B. (2007). Modeling the role of agriculture for the 20th-century global terrestrial carbon balance. Global Change Biology, 13 (3), 679-706.

[4] Boote, K. J., Jones, J. W., Hoogenboom, G., & Pickering, N. B. (1998). The CROPGRO model for grain legumes. In Understanding options for agricultural production: pp. 99-128).

[5] Boote, K. J., Jones, J. W., Mishoe, J. W., and Wilkerson, G. G., (1986). Modeling growth and yield of groundnut. Agrometeorology of Groundnut: Proceedings of an International Symposium, ICRISAT Sahelian Center, Niamey, Niger. 21/26 Aug 1985, ICRISAT, Patancheru, A. P. 502 324, India, pp. 243/ 254.

[6] Decision Support System for Agrotechnology Transfer (DSSAT) developed under the International Consortium for Agricultural Systems Applications (ICASA)". Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change. UNFCCC Nairobi Work Programme on impacts, vulnerability, and adaptation to climate change. Retrieved January 23, 2014.

[7] Fetcher, J., Allison, B. E., Sivakumar, M. V. K., van der Ploeg, R. R., and Bley, J., (1991). An evaluation of the SWATRER and CERES-Millet models for southwest Niger. In: Sivakumar, M. V. K., Wallace, J. S., Renard, C., Giroux, C. (Eds.), Soil Water Balance in the Sudano-Sahhellian Zone. International Association of Hydrological Sciences, Wallingford, UK, pp. 505–513.

[8] Gijsman, A. J; Jagtap, S. S; Jones, J. W. (2002). "Wading through a swamp of complete confusion: How to choose a method for estimating soil water retention parameters for crop models". European Journal of Agronomy. 18 (1–2): 77–106. doi: 10.1016/S1161-0301(02)00098-9.

[9] He, J., Jones, J. W., Graham, W. D., and Dukes, M. D. (2010). Influence of likelihood function choice for estimating crop model parameters using the generalized likelihood uncertainty estimation method. Agricultural Systems 103 (5), 256–64. doi: 10.1016/j.agsy.2010.01.006.

[10] Hoogenboom, G. and White, J. W. (2003). Improving physiological assumptions of simulation models by using gene-based approaches. Agronomy Journal 95 (1), 82–9. doi: 10.2134/agronj2003.0082.

[11] Hoogenboom, G., C. H. Porter, V. Shelia, K. J. Boote, U. Singh, J. W. White, L. A. Hunt, R. Ogoshi, J. I. Lizaso, J. Koo, S. Asseng, A. Singels, L. P. Moreno, and J. W. Jones. (2019). Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7.5 (https://DSSAT.net). DSSAT Foundation, Gainesville, Florida, USA.

[12] Hoogenboom, G., Wilkens, P. W., & Tsuji, G. Y. (1999). DSSAT v3, vol. 4. University of Hawaii, Honolulu, HI, 234-235.

[13] International Benchmark Sites Network for Agrotechnology Transfer. (1993). The IBSNAT Decade. Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honoluly, Hawaii.

[14] International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). 1989. The Decision Support System for Agrotechnology Transfer Version 2.1 (DSSAT v2.1) User's Guide. Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI.

[15] Jones, C. A., Kiniry, J. R., & Dyke, P. T. (1986). CERES-Maize: A simulation model of maize growth and development. Texas A& M University Press.

[16] Jones, G. Hoogenboom, C. H. Porter, K. J. Boote, W. D. Batchelor, L. A. Hunt, P. W. Wilkens, U. Singh, A. J. and, Gijsman, J. T. Ritchie. (2003). The DSSAT cropping system model. Europ. J. Agronomy 18 (2003) 235/265.

[17] Jones, g. y. Tsuji, g. Hoogenboom, l. a. Hunt, p. k. Thorntow, p. w. Wilkens, d. t. Imamura, w. t. Bowew, and u. singh. (1998). Decision support system for agrotechnology transfer: DSSAT v3.

[18] Kenneth Boote. (2020). Advances in crop modeling for sustainable agriculture, Burleigh Dodds Science Publishing, Cambridge, UK, 2019, (ISBN: 978 1 78676 240 5; www.bdspublishing.com

[19] Kihara, J., Fatondji, D., Jones, J. W., Hoogenboom, G., Tabo, R. and Bationo, A. (Eds). (2012). Improving Soil Fertility Recommendations in Africa Using the Decision Support for Agrotechnology Transfer (DSSAT). Springer, Dordrecht, the Netherlands, 195 pp. ISBN: 978-94-007-2959-9.

[20] Kim, K. S., Yoo, B. H., Shelia, V., Porter, C. H., and Hoogenboom, G. (2018). START: a data preparation tool for crop simulation models using web-based soil.

[21] Lopez, J. R., Winter, J. M., Elliott, J., Ruane, A. C., Porter, C. H. and Hoogenboom, G. (2017). Integrating growth stage deficit irrigation into a process-based crop model. Agricultural and Forest Meteorology 243 (1), 84–92. doi: 10.1016/j. agrformet.2017.05.001.

[22] Meng, Lei; Quiring, Steven M. (2008). "A Comparison of Soil Moisture Models Using Soil Climate Analysis Network Observations". Journal of Hydrometeorology. 9 (4): 641. doi: 10.1175/2008JHM916.1.

[23] Messina, C. D., Jones, J. W., Boote, K. J. and Vallejos, C. E. (2006). A gene-based model to simulate soybean development and yield responses to the environment. Crop Science 46 (1), 456–66. doi: 10.2135/cropsci2005.04-0372.

[24] Paz, J. O., Batchelor, W. D., Jones, J. W., (2003). Estimating potential economic return for variable rate soybean variety management. Trans. ASAE 46 (4), 1225–1234.

[25] Paz, J. O., Batchelor, W. D., Tylka, G. L., (2001). Estimating potential economic return for variable rate management in soybeans. Trans. ASAE 44 (5), 1335–1341.

[26] Porter, Cheryl H.; Jones, J. W.; Adiku, S.; Gijsman, A. J.; Gargiulo, O.; Naab, J. B. (2009). "Modeling organic carbon and carbon-mediated soil processes in DSSAT v4.5". Operational Research. 10 (3): 247. doi: 10.1007/s12351-009-0059-1.

[27] Quemada, M., Cabrera, M. L., (1995). CERES-N model predictions of nitrogen mineralized from cover crop residues. Soil Sci. Soc. Am. J. 59, 1059–1065.

[28] Resenes, J., Pavan, W., Holbig, C., Fernandes, J. M. and Hoogenboom, G. (2019). jDSSAT: a JavaScript module for DSSAT-CSM integration. SoftwareX 10. doi: 10.1016/j. softx.2019.100271.

[29] Ritchie, J. T., Godwin, D. C., & Otter-Nacke, S. (1988). CERES-Wheat. A simulation model of wheat growth and development. Univ. of Tex. Press, Austin.

[30] Ritchie, J. T.; U. Singh; D. C. Godwin; and W. T. Bowen. (1998). Cereal growth, development, and yield. In Understanding options of agricultural production, ed. G. Y. Tsuji, G. Hoogenboom, P. K. Thornton. Dordrecht, The Netherlands: Kluwer Academic Publishers and International Consortium for Agricultural Systems Applications. 79-98.

[31] Rosenzweig, C., Allen, L. H., Jr., Jones, J. W., Tsuji, G. Y., Hildebrand, P. (Eds.), Climate Change and Agriculture: Analysis of Potential International impacts (ASA Special Publication No. 59). Amer. Soc. Agron, Madison, WI 1995, p. 382.

[32] Singh, U., Ritchie, J. T., & Godwin, D. C. (1993). A User's Guide to CERES Rice, V2. 10. University of Ghana http://ugspace.ug.edu.gh 102 Muscle Shoals, AL, USA: International Fertilizer Development Center.

[33] Hoogenboom, G., White, J. W., Jones, J. W. and Boote, K. J. (1990). BEANGRO V1.00. Dry Bean Crop Growth Simulation Model. User's Guide. Florida Agricultural Experiment Station Journal No. N-00379. University of Florida, Gainesville, FL, 120 pp. Hoogenboom, G., Jones, J. W. and Boote, K. J. 1991. Predicting Growth and Development of Grain Legumes with a Generic Model. ASAE Hoogenboom, G., Wilkens, P. W. and Tsuji, G. Y. (Eds), DSSAT Version 3 (vol. 4). University of Hawaii, Honolulu, HI, pp. 1–36. Hoogenboom, G., White, J. W. and Messina, C. D. 2004. From genome to crop: integration through simulation modeling. Field Crops Research 90 (1), 145–63. doi: 10.1016/j.fcr.2004.07.014.

[34] Thorp, K. R.; Bronson, K. F. (2013). "A model-independent open-source geospatial tool for managing point-based environmental model simulations at multiple spatial locations". Environmental Modelling & Software. 50: 25–36. doi: 10.1016/j.envsoft.2013.09.002.

[35] Thorp, Kelly R.; Dejonge, Kendall C.; Kaleita, Amy L.; Batchelor, William D.; Paz, Joel O. (2008). "Methodology for the use of DSSAT models for precision agriculture decision support". Computers and Electronics in Agriculture. 64 (2): 276. doi: 10.1016/j.compag.2008.05.022.

[36] Tsuji, G. Y., Uehara, G. and Balas S. (eds.). (1984). DSSAT: A decision support system for agrotechnology transfer, version 3. Vols. 1, 2, and 3. University of Hawaii, Honolulu, HI.

[37] Tsuji, G. Y., (1998). Network management and information dissemination for agrotechnology transfer. In: Tsuji, G. Y., Hoogenboom, G., Thornton, P. K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 367/381.

[38] Uehara, G., & Tsuji, G. Y. (1991). Progress in crop modeling in the IBSNAT Project. Climatic Risk in Crop Production: Models and Management in the Semi-Arid Tropics and Subtropics. CAB International, Wallingford, pp. 143A/156.

[39] Uehara, G., 1998. Synthesis. In: Tsuji, G. Y., Hoogenboom, G., Thornton, P. K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 389/392.

[40] Wallach, D., Hwang, C., Correll, M. J., Jones, J. W., Boote, K. J., Hoogenboom, G., Gezan, S., Bhaktae, M. and Vallejos, C. E. (2018). A dynamic model with QTL covariables for predicting the flowering time of common bean (Phaseolus vulgaris) genotypes. European Journal of Agronomy 101 (1), 200–9. doi: 10.1016/j.eja.2018.10.003.

[41] Welch, S. M., Jones, J. W., Brennan, M. W., Reeder, G., Jacobson, B. M., (2002). PCYield: Model-Based Decision Support for PRIVATE Soybean Production. Agricultural Systems 74 (1), 79/98.

[42] White, J. W.; Hunt, L. A.; Boote, K. J.; Jones, J. W.; Koo, J.; Kim, S.; Porter, C. H.; Wilkens, P. W.; Hoogenboom, G. (2013). "Integrated description of agricultural field experiments and production: The ICASA Version 2.0 data standards". Computers and Electronics in Agriculture. 96: 1–12. doi: 10.1016/j.compag.2013.04.003.

[43] Wu, Chunlei; Anlauf, Ruediger; Ma, Youhua (2013). "Application of the DSSAT Model to Simulate Wheat Growth in Eastern China". Journal of Agricultural Science. 5 (5). doi: 10.5539/jas. v5n5p198.

[44] Yang, J. Y., Drury, C. F., Yang, J. M., Li, Z. T. and Hoogenboom, G. (2014). EasyGrapher: software for data visualization and statistical evaluation of DSSAT cropping system model and the CANB model. International Journal of Computer Theory and Engineering 6 (3), 210–4. doi: 10.7763/ IJCTE. 2014. V6.864.