Process-based crop models in soil research: a bibliometric analysis

soil systems

Review

Process-Based Crop Models in Soil Research: A Bibliometric Analysis

Eranga M. Wimalasiri [1,*], Sachini Ariyachandra [1], Aruna Jayawardhana [1], Thejani Dharmasekara [1], Ebrahim Jahanshiri [2], Nitin Muttil [3,4] and Upaka Rathnayake [5]

[1] Department of Export Agriculture, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya 70140, Sri Lanka
[2] Crops for the Future UK, National Institute of Agricultural Botany, 93 Lawrence Weaver Road, Cambridge CB3 0LG, UK
[3] Institute for Sustainable Industries & Liveable Cities, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia
[4] College of Sport, Health and Engineering, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia
[5] Department of Civil Engineering and Construction, Faculty of Engineering and Design, Atlantic Technological University, Ash Lane, F91 YW50 Sligo, Ireland
* Correspondence: eranga@agri.sab.ac.lk

Abstract: Different types of soil data are used in process-based crop models as input data. Crop models have a diverse range of applications, and soil research is one of them. This bibliographic analysis was conducted to assess the current literature on soil-related applications of crop models using two widely used crop models: Agricultural Production Systems Simulator (APSIM) and Decision Support System for Agrotechnology Transfer (DSSAT). The publications available in the Scopus database during the 2000–2021 period were assessed. Using 523 publications, a database on the application of process-based crop models in soil research was developed and published in an online repository, which is helpful in determining the specific application in different geographic locations. Soil-related applications on APSIM and DSSAT models were found in 41 and 43 countries, respectively. It was reported that selected crop models were used in soil water, physical properties, greenhouse gas emissions, N leaching, nutrient dynamics, and other physical and chemical properties related to applications. It can be concluded that a crop model is a promising tool for assessing a diverse range of soil-related processes in different geographic regions.

Keywords: agri-environmental modeling; APSIM; DSSAT; Scopus; soil systems

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1. Introduction

With the availability of fine-scale global data, the utilization of digital techniques has increased globally in environmental research. Soil science, which is a part of the Earth system, and environmental research are traditionally based on observations and analysis of observed data. However, there are different tools, approaches, and computer software that are used to assess different aspects of soil science [1–3]. Crop simulation models are one such tool to work out.

Understanding of soil processes and conservation of soil are even highlighted in the United Nation's Sustainable Development Goals (SDGs) due to their importance in the overall sustainability of the globe. For example, SDG 1 (no poverty), GDS2 (zero hunger), SDG3 (good health and well-being), SDG6 (clean water and sanitation), SDG13 (climate action), and SDG15 (life of land) can be achieved through proper understanding and management of soil aspects. Therefore, advanced tools such as crop modeling can be used to understand the soil process that will eventually contribute to the UN SDGs.

Crop models or crop simulation models are tools that use mathematical algorithms to quantify crop growth, development, and yield in interaction with the environment [4].

Using different types of environmental, management, and genetic information, crop models simulate plant and related processes [4–6]. Compared to soil research, crop modeling research is a relatively new discipline with six decades of history. After their inception in the early 1960s, they were mainly used to simulate the response of crop growth and yield to environmental factors [4]. They are also used as research tools in decision making and for educational purposes [7]. Even though the major application of crop simulation models is the simulation of plant processes, they were used in several other crop-associated processes. For example, these crop models were used to study climate change impacts and adaptation [8,9], agroforestry systems [10], greenhouse gas emissions [11], farm economics [12], farming system simulations [5], and many more [5,13]. In addition, several attempts were reported on the simulation of different soil-related processes and parameters using crop models; nitrogen dynamics [14,15], carbon dynamics [16,17], greenhouse gas emission [18,19], soil water and water use efficiency [20,21], other physicochemical properties [22–24] and as part of a decision support system for farming [5,25]. Integration of crop models for mapping and yield estimation at the country/regional level is gaining popularity, which includes soil as input data [26].

Soil physical, chemical, and biological properties are equally important for the performance of the soil and farming systems and the overall sustainability of the agroecosystems. Out of many properties, some chemical properties such as pH, cation exchange capacity, nitrogen, organic matter/carbon, and physical properties that include bulk density, soil moisture at different pressure levels (permanent wilting point, drainage upper limit), and texture are used as input data in crop models to simulate crop growth, development, and yield [5,13]. Different crop model outputs have their own sensitivities to soil properties [27]. Therefore, soil in crop models is two-fold, as an input to run the model and as an output after simulations.

There are several process-based crop models with different complexities and capabilities [28]. They are also different in input data, processing types, and outputs. Out of them, Agricultural Production Systems sIMulator (APSIM) [5,25] and Decision Support System for Agrotechnology Transfer (DSSAT) [6,29] are two major and widely used crop models. The applications of both APSIM and DSSAT models were documented by several authors [5,6].

Documentation and analysis of available information on the soil-related applications of crop models are important to practitioners, policymakers, or anyone interested in soil-related aspects. Bibliometric analysis is a popular method that can be used to explore and analyze a large set of scientific publications [30–32]. Analyzing and visualizing bibliometric networks, which are also known as science mapping [31], is gaining popularity and being used in several research fields [30]. Bibliometric analyses are important in order to understand the current overview and trends of publications, evaluate the contribution of literature to the field, identify gaps in the relevant field/publications, and develop novel ideas for further investigation [30]. Bibliometric analysis is gaining popularity among publishers, funding agencies, and research institutions [31]. However, the soil-related applications in crop models were not studied using bibliometric or science mapping previously.

There is enough evidence to suggest that crop models are multipurpose in nature and extensively used in soil-related studies. However, the use of crop models in soil research was not studied in detail. In addition, a proper review and bibliometric analysis of published literature on crop models on soil applications are important in model development and future decision making regarding crop modeling. Therefore, the objective of this paper is to analyze the literature on applications of crop models in soil research using bibliometric analysis. Further, the data are published in an open repository as a database that can be used to determine the diversity and capabilities of crop simulation models in soil-related research in the future. The open repository will be an excellent addition to any related future studies in achieving SDGs and then bringing food security in a global sense. Therefore, the authors are expected to showcase the state of the art of crop models available in the literature; thus, the outcome can effectively be used for any further research work.

2. Materials and Methods

2.1. Data Source and Data

Extensive datasets with an adequate number of records for a certain period are needed for the bibliometric analyses. In order to maintain the quality of data, publications available in the Scopus database (www.scopus.com; accessed on 28 December 2022) were used, and the publication during the 2000–2021 period was considered in this study. The title, abstract, and keywords were evaluated in the "Scopus" search. Accordingly, the following search criteria were used to obtain the publication details.

TITLE-ABS-KEY ((APSIM OR (Agricultural Production Systems Simulator)) AND soil) AND PUBYEAR > 1999 AND PUBYEAR < 2022

TITLE-ABS-KEY ((DSSAT OR (Decision Support System for Agrotechnology Transfer)) AND soil) AND PUBYEAR > 1999 AND PUBYEAR < 2022

TITLE-ABS-KEY ((Aquacrop AND soil) AND PUBYEAR > 1999 AND PUBYEAR < 2022

Then, the relevance of the publication to the topic of interest was manually evaluated, and irrelevant publications were removed. The removed publications include sources that mention soil data as input files. The screened publications were used for further analysis.

2.2. Analysis and Visualization

2.2.1. Analysis

Several tools and methods are used to perform the bibliometric analysis [30]. Different types of analysis methods were used in this study that covers major categories of bibliometric analysis; performance analysis, science mapping, and network mapping as follows.

Citation-Related Metrics

Normalized citations—Since the publications were distributed throughout the period, the generalization of citations in terms of average and total citations can lead to misleading values. To avoid this issue and to remove the impact of the number of years from the date of publication, normalized citations were calculated as follows [33].

$$\text{Nomalized citations} = \frac{\text{Total no. of citations}}{\text{No. of years from the published year}} \tag{1}$$

CiteScore

The recent CiteScore available in the Scopus database (the year 2021) was used in this study. The CiteScore of 2021 counts the total citations received for the publications during the 2018–2021 period, which was divided by the number of published documents [34].

Other types of bibliometric analysis performed in this study include bibliographic coupling, network analysis, clustering, co-work analysis, and keyword analysis. Bibliographic coupling occurs when two research documents cite the same reference (already published paper). This was introduced by Kessler [35]. More information on bibliographic coupling can be found in Jarneving et al. [36]. Citation network analysis maps related research as citation practice. It is a review method to quantitatively present the research work. It also provides the citation timeline of the research work too. More information on citation network analysis can be found in McLaren and Bruner [37]. The principle and the analysis procedure of these methods are described in detail by Donthu et al. [30].

2.2.2. Visualization

The network mapping, bibliographic coupling, keyword analysis, and visualizations were performed using VOSviewer version 1.6.18 [32,38,39]. VOSviewer is a software that can be used in visualizing bibliometric networks. It can create bibliometric networks and has advanced layout and clustering techniques and natural language processing techniques. The text mining option is used in co-occurrence networks and keyword analysis [39]. In the visualizations, different clusters were marked in different colors.

2.3. Development of a Database

In the selected papers used in the analysis (Section 2.2), the soil-related application, geographic location, and major type of application mentioned in the publications were evaluated as the next step and documented. The dataset was used to develop a database on crop model applications in soil research.

3. Results

3.1. Performance Analysis

The Scopus search found 1446 publications, 660 on APSIM, 299 on AquaCrop, and 487 on the DSSAT model. After the manual screening of publications on applications of soil science, a total of 523 articles were remained (336 APSIM and 187 DSSAT) and used in the analysis. The selection of APSIM or DSSAT or other crop models depends on the preference and the expertise of the researcher, along with the input data and intended use/application of the model.

Being a water-driven model, AquaCrop applications are mainly on soil water balance, evapotranspiration, and water use efficiency; therefore, the AquaCrop model was not used in the analysis described in this paper. The number of publications on both models (APSIM and DSSAT) showed an increasing trend, while the highest number of publications was from the most recent year (2021). In the year 2021, 39 and 21 publications were published on APSIM and DSSAT models, respectively. The highest number of publications belongs to the last decade (2012–2021), where 75.6% of APSIM and 69% of DSSAT-related documents were published. The variation of publications throughout time is shown in Figure 1. Around 91% of soil-related crop modeling papers in the Scopus database were published in peer-reviewed journals (Figure 2).

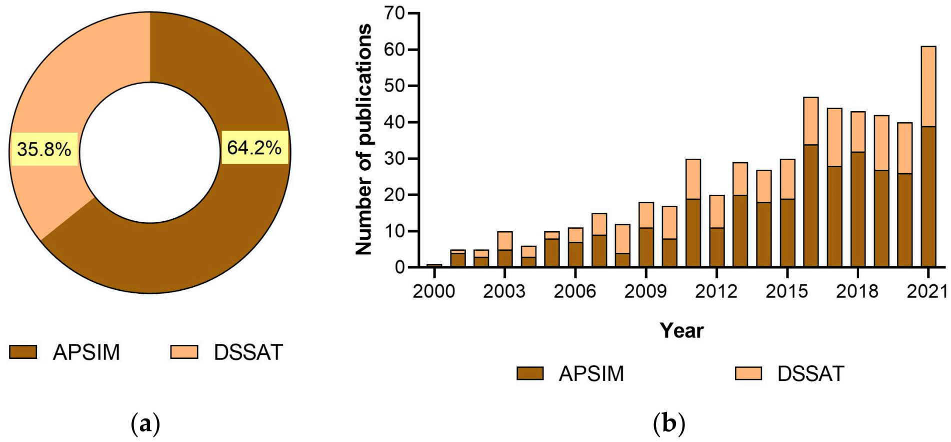


Figure 1. (**a**) The composition of publications and (**b**) the variation of publications throughout the 2000–2021 period.

3.2. Geographic Distribution of Applications

Soil-related applications using the APSIM and DSSAT models were conducted in 58 countries. Out of all, APSIM-related applications are found in 41 countries, whereas DSSAT applications are available in 43 countries (Figure 3). The highest number of APSIM publications were reported from Australia, followed by China and New Zealand, while DSSAT publications were reported from the USA (Figure 3).

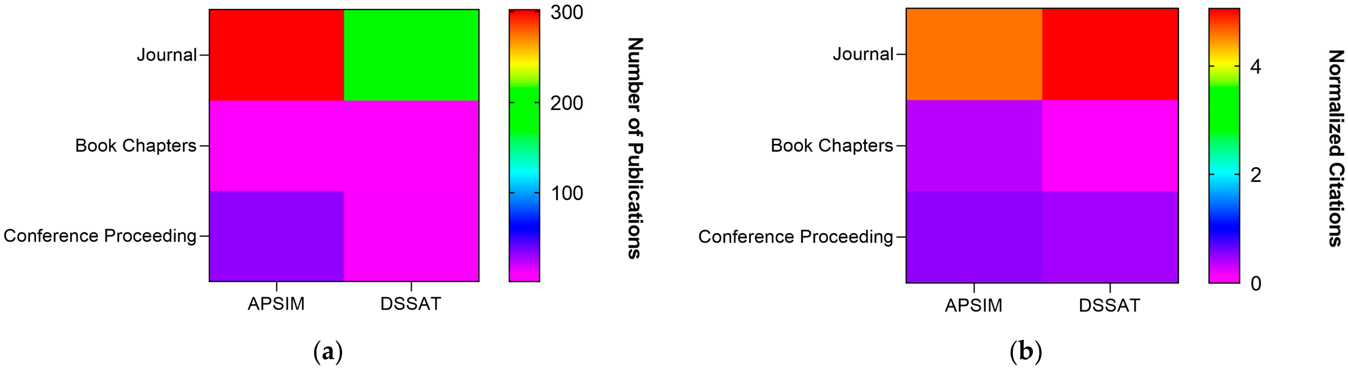


Figure 2. The composition of (**a**) number of publications and (**b**) normalized citations of each publication category in APSIM and DSSAT models.

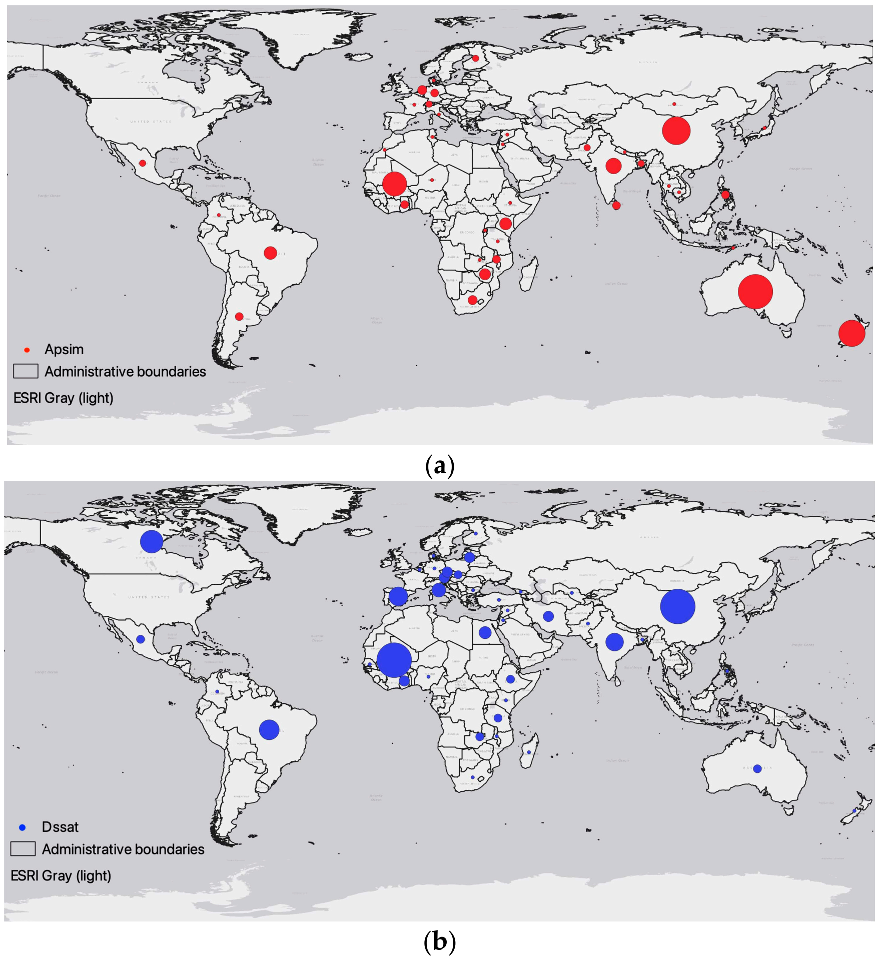


Figure 3. Geographic distribution of (**a**) APSIM and (**b**) DSSAT applications in soil research.

3.3. Citation Analysis

Summary statistics of the citations and normalized citations are mentioned in Table 1. The DSSAT model has relatively higher mean citations (30.8) and mean normalized citations (4.7) than the APSIM model. Even though the number of publications is lower for DSSAT than the APSIM, the median and 75th percentiles of both citations and normalized citations are higher in DSSAT than in the other model (refer to Table 1). On average, journal publications received a comparatively higher number of citations and normalized citations than other types of publications.

Table 1. Summary statistics of the citations and normalized citations.

Parameter	Citations		Normalized Citations	
	APSIM	DSSAT	APSIM	DSSAT
Mean	24.0	30.8	4.2	4.7
Std. Deviation	26.5	38.4	4.7	5.8
25% Percentile	7.0	6.0	1.1	1.2
Median	15.0	20.0	3.0	3.4
75% Percentile	33.0	41.0	6.0	5.8
Range	0–195	0–238	0–54	0–48

3.4. Sources and Their Impact

A total of 108 and 78 sources reported soil-related applications in APSIM and DSSAT models, respectively. According to the number of publications, Field Crops Research, Agricultural Systems, and Agricultural Water Management journals ranked top in the APSIM model (refer to Table 2). Based on the averaged normalized citations (per journal), the top three journals are Crop Science (29), Scientific Reports (27.5), and Journal of Experimental Botany (11.4). The top 20 sources of each model, according to the averaged normalized citations (per journal), are mentioned in Appendix A Table A1. In the DSSAT model, Agricultural Water Management, Transactions of the ASABE, and Agronomy Journal ranked the top 3 sources with the highest number of papers (Table 3). According to the averaged normalized citations (per journal) of the DSSAT model, Remote Sensing of Environment (26.4), Soil and Tillage Research (11.4), and Field Crops Research (10.7) ranked top.

Table 2. Sources with the highest number of publications in the APSIM model.

Source	Number of Publications	Average Normalized Citations
Field Crops Research	42	5.2
Agricultural Systems	23	5.2
Agricultural Water Management	23	4.4
European Journal of Agronomy	18	5.3
Agriculture, Ecosystems and Environment	13	7.8
Australian Journal of Agricultural Research	12	2.3
Agricultural and Forest Meteorology	10	5.6
Geoderma	9	3.8
Crop and Pasture Science	8	2.6
Science of the Total Environment	8	8.2
Soil Research	8	2.7

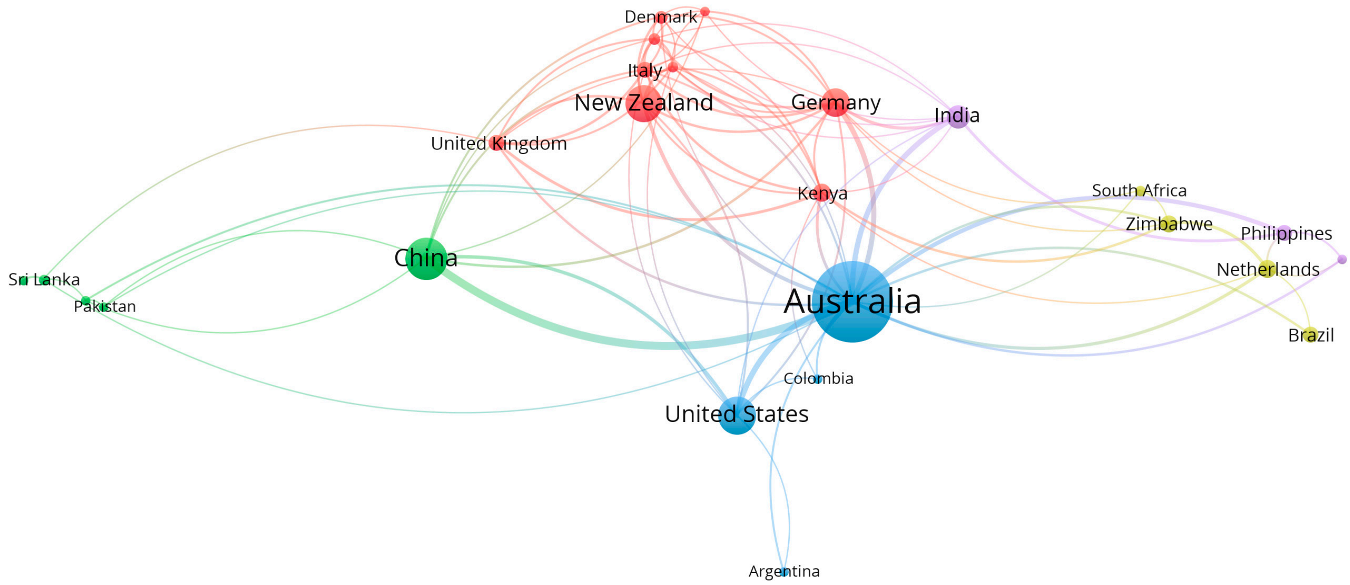
Table 3. Sources with the highest number of publications in the DSSAT model.

Source	Number of Publications	Average Normalized Citations
Agricultural Water Management	36	8.5
Transactions of the ASABE	16	3.6
Agronomy Journal	13	3.4
Agricultural Systems	9	4.0
European Journal of Agronomy	7	8.0
Field Crops Research	7	10.7
Nutrient Cycling in Agroecosystems	5	4.0
Agricultural and Forest Meteorology	4	5.7
Journal of Agricultural Science	3	3.9
Journal of Integrative Agriculture	3	3.3

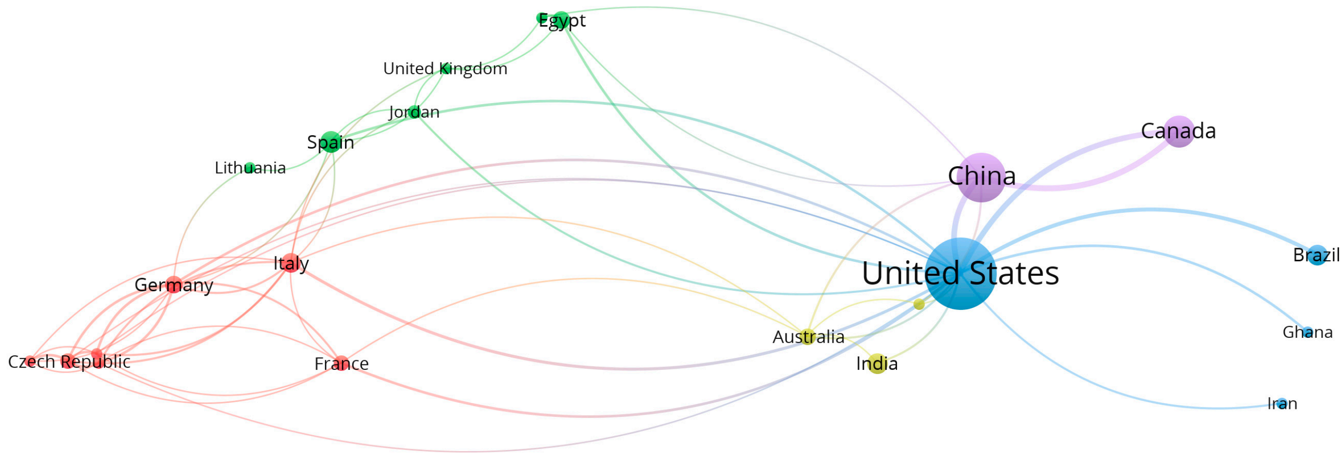
3.5. Relationships among Soil-Related Crop Modeling Publications

3.5.1. Collaboration

The collaborative network of countries in soil-related crop modeling applications is shown in Figure 4a (for APSIM) and Figure 4b (for DSSAT), where a higher collaboration strength can be observed between the countries in the same cluster. The collaborative country network revealed that there are 53 and 52 countries for APSIM and DSSAT models, respectively. In the APSIM model, there were 25 countries with more than 3 publications, whereas 22 countries for the DSSAT model were under the same criteria.



(**a**)



(**b**)

Figure 4. The collaborative country network on soil-related applications in (**a**) APSIM and (**b**) DSSAT models.

There are five clusters for APSIM collaborative network, and Germany, China, Australia, Netherlands, and India ranked top in each cluster. Australia has had the highest total link strength among all the countries since APSIM was developed there. As shown in Figure 4, there are five clusters for DSSAT collaborative network, and the United States has the highest total link strength. Germany (cluster 1), Egypt and Spain (cluster 2), the United

States (cluster 3), Australia (cluster 4), and China (cluster 5) had the highest link strength in each cluster.

3.5.2. Co-Occurrence of Author Keywords

In the APSIM, out of the 875 author keywords, 49 of them appeared a minimum of 5 times. Out of the 49 selected keywords with the highest appearance, nitrogen, evapotranspiration, water use efficiency, carbon sequestration, and nitrate leaching ranked 6, 7, 10, 11, and 12, respectively (refer to Appendix A Table A2). In the DSSAT, out of 516 author keywords, 34 appeared a minimum of 5 times, where soil moisture, water use efficiency, and evapotranspiration ranked 4, 6, and 8, respectively (Appendix A Table A2). The link between author keywords is shown in Figure 5. Generally, it is evident that the authors used some soil-related keywords as author keywords.

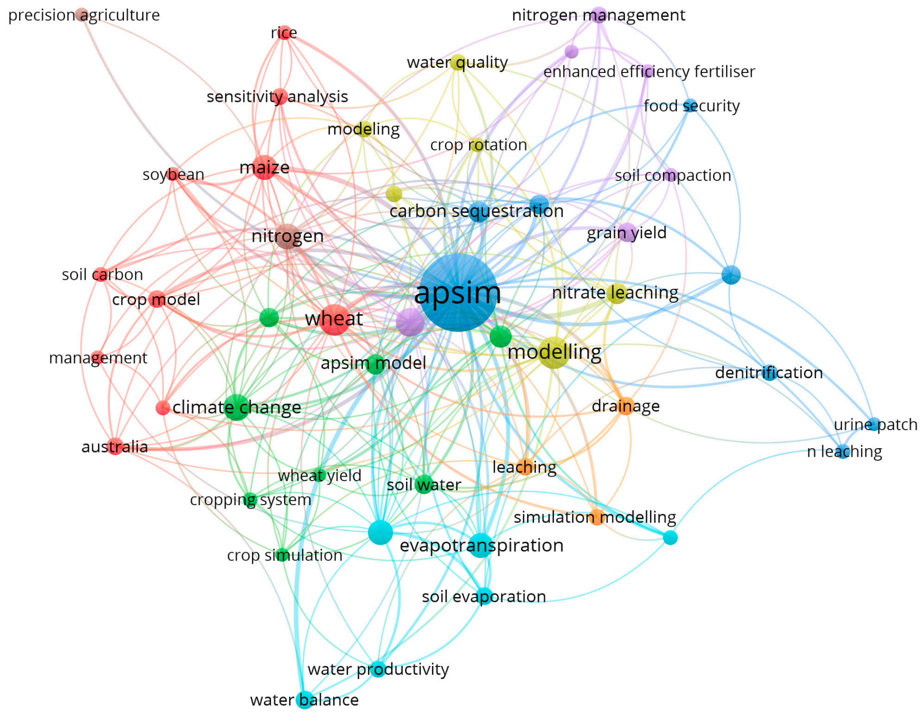
3.6. *Keywords from Abstracts*

Out of the 10,195 terms in the abstracts, 54 appeared more than 50 times in APSIM-related papers, while 17 terms appeared more than 100 times. In DSSAT, out of 5906 terms, 21 terms appeared more than 50 times, while there are 4 terms that appeared more than 100 times. Soil-related terms such as PAWC (plant available water content), SOC (soil organic carbon), N_2O emission, deep drainage, temperature, soil moisture, soil, and soil water content terms showed higher relevance scores compared to other terms. Interestingly, the top two terms in APSIM were plant available water content and soil organic carbon. The top 20 terms based on the relevance score, which were extracted from abstracts, are shown in Table 4.

Table 4. Top 20 keywords found in abstracts based on the relevance score.

Rank	APSIM			DSSAT		
	Term	Relevance Score	Occurrences	Term	Relevance Score	Occurrences
1	PAWC *	5.71	79	Model	4.91	707
2	SOC *	3.84	97	Soil moisture	2.48	85
3	Emission	3.08	138	Irrigation	1.53	163
4	N_2O emission	2.75	128	Yield	1.43	346
5	Deep drainage	2.55	69	Soil	1.29	177
6	Temperature	2.43	149	Soil water content	1.18	78
7	Climate	1.85	119	Water	1.08	200
8	Drainage	1.82	85	Treatment	0.94	159
9	Rainfall	1.74	179	DSSAT	0.73	185
10	Sowing	1.73	86	Simulation	0.71	149
11	Crop yield	1.42	119	Study	0.63	187
12	Maize	1.32	99	Grain yield	0.61	69
13	Season	1.25	199	Agrotechnology transfer	0.53	70
14	Irrigation	1.25	133	Data	0.51	188
15	Climate change	1.22	71	Decision support system	0.47	99
16	N leaching	1.21	69	Maize	0.44	117
17	N loss	1.21	64	Effect	0.41	117
18	Change	1.20	155	Season	0.33	95
19	Yield	1.18	579	Crop yield	0.29	62
20	Soil water	1.09	96	Crop	0.25	132

* PAWC = plant available water content, SOC = soil organic carbon, DSSAT = Decision Support System for Agrotechnology Transfer.



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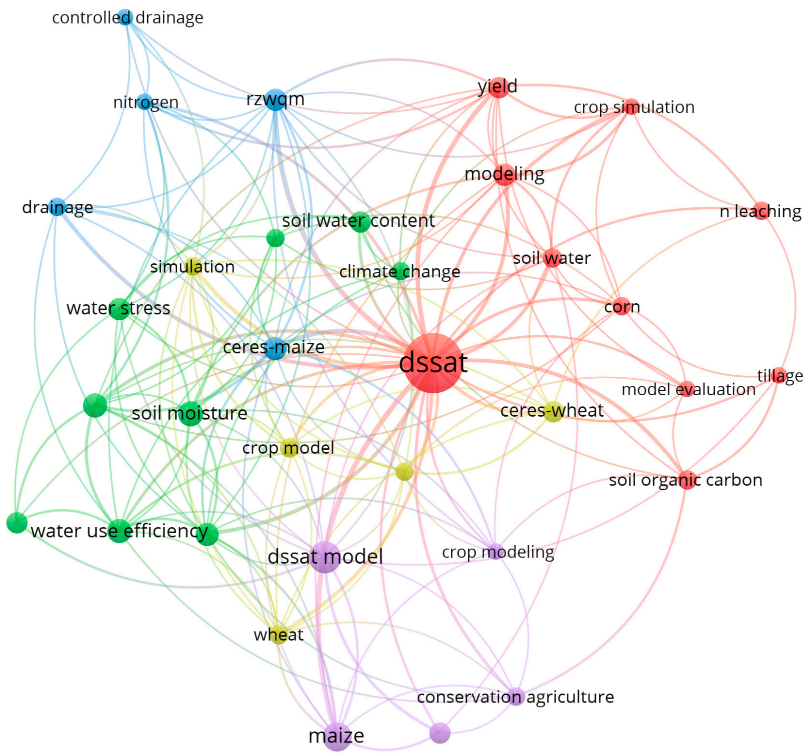

(**b**)

Figure 5. Author keywords in soil-related research conducted using (**a**) APSIM and (**b**) DSSAT models.

When considering both models together, out of 14,352 terms, 96 appeared more than 50 times, while 29 terms appeared more than 100 times (refer to Figure 6). Out of them, soil-related terms such as soil organic carbon, soil, water, soil water, and nitrogen ranked 2, 9, 11, 19, and 27, respectively, which suggests the use of soil terms in the abstracts.

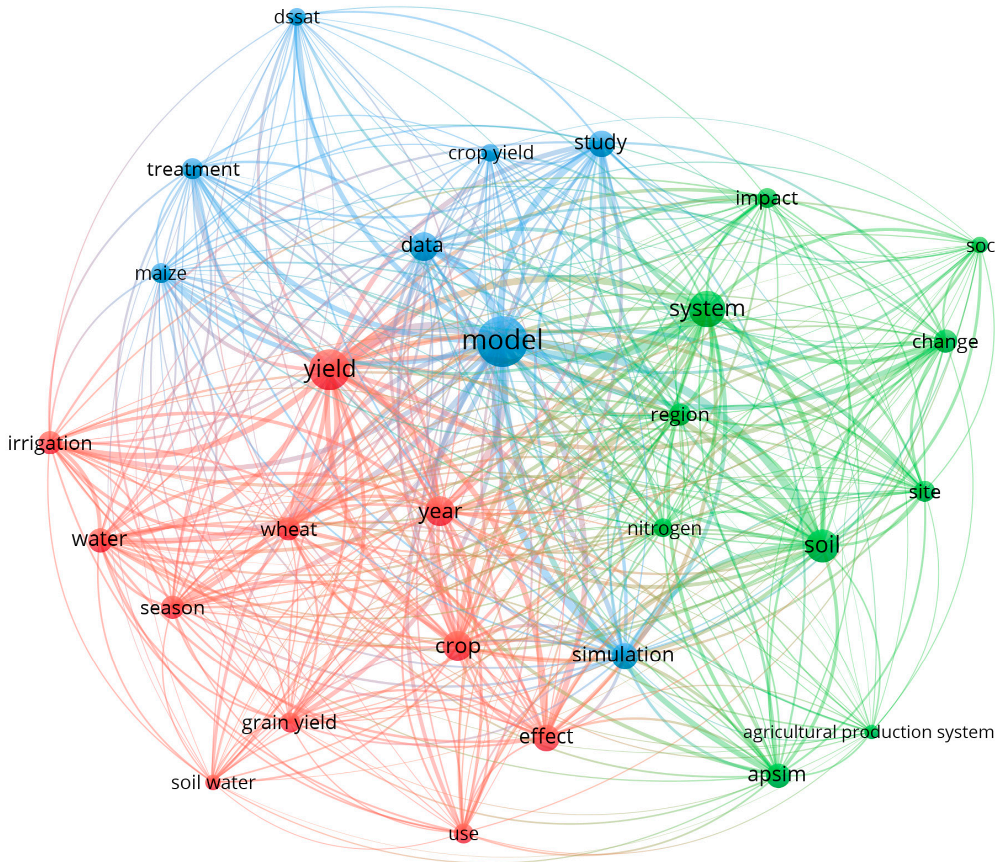

Figure 6. Author keywords extracted from abstracts—both models.

3.7. *Applications of Crop Models in Soil Research*

Soil-related applications of APSIM and DSSAT crop models are shown in Figure 7. Similar types of applications were categorized into clusters to identify the major applications. For example, soil water balance, drainage, and water use efficiency were clustered under soil water, while soil compaction, permeability, and other physical properties that do not belong to major classes were clustered into physical properties. In addition, greenhouse gas emission (GHG) includes N_2O, CH_4, and CO_2 emissions. It is evident that the APSIM model (15 types) has a relatively higher number of application types than the DSSAT model (11 types). In both models, the highest number of applications were reported on soil water-related publications (215 and 127 in APSIM and DSSAT models, respectively), followed by N dynamics (129 and 45) and organic carbon (87 and 31). Other than that, both models were used to study N leaching, evapotranspiration, nutrient dynamics, P dynamics, physical properties, soil productivity, and temperature. APSIM model also was used to simulate GHG emission from soils and K dynamics (Figure 7).

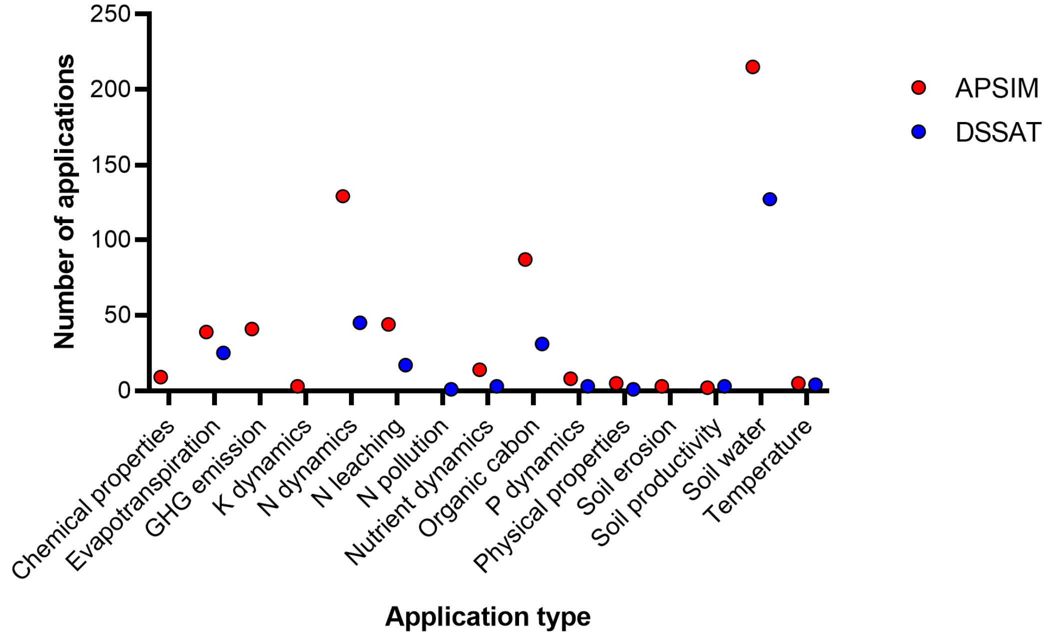

Figure 7. Soil-related applications of APSIM and DSSAT models.

3.8. Database on Soil-Related Applications of APSIM and DSSAT Models

A database on the application of process-based crop models in soil research was developed and published in an online repository (doi: 10.17632/8yh57yxcrw.1, accessed on 23 February 2023). This database contains details on the title, authors, source of publication and the published year, crop model and associated module in each model (if any), geographic location of application and the major application type. The initial version of the database contains details on publications on APSIM and DSSAT models during the 2000–2021 period only. However, it is expected to improve the database with other crop models, and the database will be updated with recent data. The database can be used to obtain an idea of the specific application in different geographic locations.

4. Discussion

The data from the Scopus analysis illustrates that for 21 years (until the year 2021), several applications of soil-related processes were implemented using process-based crop models. However, soil-related applications of crop models have a limited number of publications when compared with the total number of publications of the selected models (data not presented here). This review reveals that soil-related applications in crop models have significantly increased in the last decade of study (2012–2021), with over 70% of publications appearing for that period. Therefore, this positive trend suggests the use of crop models in soil research for future studies. This increased number of publications can be accelerated after the development of soil-associated modules [40] and/or modifications in the traditional/regular crop models.

Out of the two models studied in detail, Agricultural Production Systems Simulator (APSIM) has a more diverse range of applications than the Decision Support System for Agrotechnology Transfer (DSSAT) model. This is proven by the fact that the number of publications is also higher for APSIM than for DSSAT. However, other than the crop models reviewed here, there are other crop models with specific soil-related capabilities and applications. For example, the ARMOSA crop model was used to simulate NO3-N leaching from agricultural systems [40]. AquaCrop [41,42], the model omitted in the analysis, is a water-driven model that is mainly used to simulate soil water-related conditions. Therefore, two widely used crop models were used in this paper to assess the applications of crop models in soil research as a case study. Even though there are several crop models with different capabilities and applications, only APSIM and DSSAT models were assessed here, which is a limitation of the current study. It is important to assess the soil-related applications of other crop models and strengthen the database.

Also, there are stand-alone soil models such as QUantifying Interactions between terrestrial Nutrient CYcles and the climate system (QUINCY) [43] and Jena Soil Model (JSM) [44] with high capacities to simulate complex soil properties. The possibility of combining these specific soil models with crop models is important, which creates new research avenues. Other than the crop- and soil-related process, these crop models can be used in other agri-environmental-related studies. For example, the inclusion of soil water components in crop models is beneficial in climate change studies [45]. As it was already stated, food production in the world to date is in scarcity due to ongoing climate change. Therefore, the possibility of combining process-based crop models in a wider range of environmental research should be assessed in detail.

The collaborative country network was developed in this study (refer to Figure 4). It is important to promote the publications and collaborations between researchers from developing and developed countries in crop model applications in soil research. Since the applications are available for limited countries, it is also important to popularize crop model applications in other countries. Dissemination of knowledge in the related studies would enhance food sustainability in developing countries. The published database can be used to determine the suitable model for a specific region and discipline of interest.

According to this review, researchers have explored various aspects of soil-related processes in crop models that ranged from nutrient dynamics, water, greenhouse gas emission, and other physical and chemical properties (Figure 7). Not only the plant processes but also performance in livestock farms were also assessed. The main purpose of some of the publications was to study the soil-related processes [14,46–50], and in most of the publications, it was either documented as supportive output to evaluate any other plant-related processes. The developed database can be used in selecting crop models/supporting modules for various types of applications, such as soil nutrient dynamics, GHG emissions, and other soil physicochemical applications in different geographic regions.

Another limitation of the study is the less perfect bibliometric analysis results due to the use of one database [51]. There are few other literature databases other than Scopus. Therefore, it is expected to improve the current dataset using more data obtained from the other literature databases, such as Web of Science, PubMed, Directory of Open Access Journals (DOAJ), and Chinese National Knowledge Infrastructure (CKNI), etc., for the future study. The information from other databases can then be used to perform a comprehensive review and strengthen the developed database. Further, limitations with the accessibility to some of the databases hinder such applications.

Bibliometric analysis is an important tool that was used to assess the global scientific production on soil-related applications of two widely used crop models; APSIM and DSSAT. It can be used to assess the intellectual structure of a specific field of interest and detect patterns of publications and different types of networking [52]. The indicators used in this study are an indication of the impact and the importance of the work tested here, where a wider research community can get benefits. The findings of collaboration and country networks can be used in designing collaborative research and funding applications. This will also create several research avenues, such as detailed soil-related applications, agri-environmental modeling, multi-model comparisons, and model strengthening and development.

5. Conclusions

The bibliometric analysis conducted in this study determined the applications and trends of process-based crop models in soil research. This research was carried out to fill the research gap in providing a bibliometric analysis on collaboration and applications of crop models in different geographic regions. The generated collaborative country network and keyword maps revealed the collaboration between countries and different terms used in soil-related research in crop modeling. A database on the application of process-based crop models in soil research was developed and published in an online repository that can be used to determine the specific application of crop models in different geographic locations. The knowledge gaps in soil-related applications of crop models were identified through the bibliometric analysis conducted in this study, which can be addressed through further research. The publications reviewed here have indicated that the crop models could be successfully used as a decision support tool in soil-related research.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Sources with the highest number of averaged normalized citations in APSIM and DSSAT models.

Rank	APSIM			DSSAT		
	Source	ANC *	No. of Publications	Source	ANC *	No. of Publications
1	Crop Science	29.0	1	Remote Sensing of Environment	26.4	1
2	Scientific Reports	27.5	2	Soil and Tillage Research	11.4	2
3	Journal of Experimental Botany	11.4	3	Field Crops Research	10.7	7
4	Ecological Economics	11.0	1	Agricultural Research	10.3	1
5	Journal of Agriculture and Food Research	11.0	1	Journal of Hydrology and Hydromechanics	10.3	1
6	Global Change Biology	8.8	2	Computers and Electronics in Agriculture	9.3	2
7	Environmental Research Letters	8.5	4	Agricultural Water Management	8.5	36
8	Science of the Total Environment	8.2	8	PLoS ONE	8.3	1
9	In Silico Plants	8.0	1	European Journal of Agronomy	8.0	7
10	Agriculture, Ecosystems and Environment	7.8	13	Stochastic Environmental Research and Risk Assessment	8.0	1
11	Acta Agriculturae Scandinavica Section B: Soil and Plant Science	7.0	1	Operational Research	6.4	1
12	Computers and Electronics in Agriculture	7.0	1	Journal of Hydrology	6.0	1
13	Journal of Geophysical Research: Biogeosciences	7.0	1	Agricultural and Forest Meteorology	5.7	4
14	Theoretical and Applied Climatology	7.0	2	Ecological Modelling	5.2	2
15	Ecological Modelling	6.8	1	Science of the Total Environment	5.0	1
16	Agronomy Journal	6.6	3	European Journal of Soil Science	4.5	1
17	Journal of Hydrology	6.5	2	Environmental Modelling and Software	4.4	1
18	Journal of Agricultural Science	6.4	2	Geoderma	4.1	1
19	Frontiers in Plant Science	6.2	5	Journal of Cleaner Production	4.0	1
20	Climatic Change	5.6	1	Nutrient Cycling in Agroecosystems	4.0	5

* ANC = average normalized citations.

Table A2. Rank of author keywords based on the occurrence.

Rank	APSIM			DSSAT		
	Keyword	**Occurrences**	**Total Link Strength**	**Keyword**	**Occurrences**	**Total Link Strength**
1	apsim	156	226	dssat	65	112
2	modelling	27	44	dssat model	18	18
3	wheat	25	43	maize	15	23
4	simulation	21	43	soil moisture	12	16
5	climate change	18	31	irrigation	11	21
6	nitrogen	17	35	water use efficiency	11	19
7	evapotranspiration	16	23	ceres-maize	10	23
8	maize	16	27	evapotranspiration	10	22
9	yield	16	33	modeling	9	18
10	water use efficiency	13	21	rzwqm	9	24
11	carbon sequestration	12	28	water stress	9	10
12	nitrate leaching	12	26	ceres-wheat	8	13
13	apsim model	11	11	sensitivity analysis	8	9
14	grain yield	10	13	soil water content	8	7
15	irrigation	10	19	winter wheat	8	8
16	nitrous oxide	10	15	yield	8	23
17	soil organic carbon	10	23	crop model	7	12
18	soil water	10	19	soil organic carbon	7	13
19	drainage	9	20	soil water	7	15
20	water balance	9	16	wheat	7	16

References

1. García-Díaz, A.; Bienes, R.; Sastre, B.; Novara, A.; Gristina, L.; Cerdà, A. Nitrogen Losses in Vineyards under Different Types of Soil Groundcover. A Field Runoff Simulator Approach in Central Spain. *Agric. Ecosyst. Environ.* **2017**, *236*, 256–267. [CrossRef]
2. Palliyaguru, C.; Basnayake, V.; Makumbura, R.K.; Gunathilake, M.B.; Muttil, N.; Wimalasiri, E.M.; Rathnayake, U. Evaluation of the Impact of Land Use Changes on Soil Erosion in the Tropical Maha Oya River Basin, Sri Lanka. *Land* **2023**, *12*, 107. [CrossRef]
3. Archontoulis, S.V.; Miguez, F.E.; Moore, K.J. Evaluating APSIM Maize, Soil Water, Soil Nitrogen, Manure, and Soil Temperature Modules in the Midwestern United States. *Agron. J.* **2014**, *106*, 1025–1040. [CrossRef]
4. Asseng, S.; Zhu, Y.; Basso, B.; Wilson, T.; Cammarano, D. Simulation Modeling: Applications in Cropping Systems. In *Encyclopedia of Agriculture and Food Systems*; Van Alfen, N.K., Ed.; Academic Press: Oxford, UK, 2014; pp. 102–112, ISBN 978-0-08-093139-5.
5. Holzworth, D.P.; Huth, N.I.; deVoil, P.G.; Zurcher, E.J.; Herrmann, N.I.; McLean, G.; Chenu, K.; van Oosterom, E.J.; Snow, V.; Murphy, C.; et al. APSIM—Evolution towards a New Generation of Agricultural Systems Simulation. *Environ. Model. Softw.* **2014**, *62*, 327–350. [CrossRef]
6. Jones, J.W.; Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Batchelor, W.D.; Hunt, L.A.; Wilkens, P.W.; Singh, U.; Gijsman, A.J.; Ritchie, J.T. The DSSAT Cropping System Model. *Eur. J. Agron.* **2003**, *18*, 235–265. [CrossRef]
7. Kasampalis, D.A.; Alexandridis, T.K.; Deva, C.; Challinor, A.; Moshou, D.; Zalidis, G. Contribution of Remote Sensing on Crop Models: A Review. *J. Imaging* **2018**, *4*, 52. [CrossRef]
8. Bassu, S.; Brisson, N.; Durand, J.-L.; Boote, K.; Lizaso, J.; Jones, J.W.; Rosenzweig, C.; Ruane, A.C.; Adam, M.; Baron, C.; et al. How Do Various Maize Crop Models Vary in Their Responses to Climate Change Factors? *Glob. Chang. Biol.* **2014**, *20*, 2301–2320. [CrossRef]
9. Lobell, D.B.; Asseng, S. Comparing Estimates of Climate Change Impacts from Process-Based and Statistical Crop Models. *Environ. Res. Lett.* **2017**, *12*, 015001. [CrossRef]
10. Ivezić, V.; Yu, Y.; Werf, W.V.D. Crop Yields in European Agroforestry Systems: A Meta-Analysis. *Front. Sustain. Food Syst.* **2021**, *5*, 606631. [CrossRef]
11. Thorburn, P.J.; Biggs, J.S.; Collins, K.; Probert, M.E. Using the APSIM Model to Estimate Nitrous Oxide Emissions from Diverse Australian Sugarcane Production Systems. *Agric. Ecosyst. Environ.* **2010**, *136*, 343–350. [CrossRef]
12. Bai, Y.; Gao, J. Optimization of the Nitrogen Fertilizer Schedule of Maize under Drip Irrigation in Jilin, China, Based on DSSAT and GA. *Agric. Water Manag.* **2021**, *244*, 106555. [CrossRef]

13. Wimalasiri, E.M.; Ashfold, M.J.; Jahanshiri, E.; Walker, S.; Azam-Ali, S.N.; Karunaratne, A.S. Agro-Climatic Sensitivity Analysis for Sustainable Crop Diversification; the Case of Proso Millet (*Panicum miliaceum* L.). *PLoS ONE* **2023**, *18*, e0283298. [CrossRef] [PubMed]
14. Vogeler, I.; Cichota, R.; Langer, S.; Thomas, S.; Ekanayake, D.; Werner, A. Simulating Water and Nitrogen Runoff with APSIM. *Soil Tillage Res.* **2023**, *227*, 105593. [CrossRef]
15. Singh, S.; Bhattarai, R.; Negm, L.M.; Youssef, M.A.; Pittelkow, C.M. Evaluation of Nitrogen Loss Reduction Strategies Using DRAINMOD-DSSAT in East-Central Illinois. *Agric. Water Manag.* **2020**, *240*, 106322. [CrossRef]
16. Liu, D.L.; O'Leary, G.J.; Ma, Y.; Cowie, A.; Li, F.Y.; McCaskill, M.; Conyers, M.; Dalal, R.; Robertson, F.; Dougherty, W. Modelling Soil Organic Carbon 2. Changes under a Range of Cropping and Grazing Farming Systems in Eastern Australia. *Geoderma* **2016**, *265*, 164–175. [CrossRef]
17. Chauhan, Y.S.; Thorburn, P.; Biggs, J.S.; Wright, G.C.; Chauhan, Y.S.; Thorburn, P.; Biggs, J.S.; Wright, G.C. Agronomic Benefits and Risks Associated with the Irrigated Peanut–Maize Production System under a Changing Climate in Northern Australia. *Crop Pasture Sci.* **2015**, *66*, 1167–1179. [CrossRef]
18. Wang, G.; Luo, Z.; Wang, E.; Zhang, W. Reducing Greenhouse Gas Emissions While Maintaining Yield in the Croplands of Huang-Huai-Hai Plain, China. *Agric. For. Meteorol.* **2018**, *260–261*, 80–94. [CrossRef]
19. Meier, E.A.; Thorburn, P.J.; Kragt, M.E.; Dumbrell, N.P.; Biggs, J.S.; Hoyle, F.C.; van Rees, H. Greenhouse Gas Abatement on Southern Australian Grains Farms: Biophysical Potential and Financial Impacts. *Agric. Syst.* **2017**, *155*, 147–157. [CrossRef]
20. Zeleke, K.T.; Anwar, M.; Liu, D.L. Managing Crop Stubble during Fallow Period for Soil Water Conservation: Field Experiment and Modelling. *Env. Earth Sci.* **2014**, *72*, 3317–3327. [CrossRef]
21. Chimonyo, V.G.P.; Wimalasiri, E.M.; Kunz, R.; Modi, A.T.; Mabhaudhi, T. Optimizing Traditional Cropping Systems Under Climate Change: A Case of Maize Landraces and Bambara Groundnut. *Front. Sustain. Food Syst.* **2020**, *4*, 562568. [CrossRef]
22. Adam, M.; Dzotsi, K.A.; Hoogenboom, G.; Traoré, P.C.S.; Porter, C.H.; Rattunde, H.F.W.; Nebie, B.; Leiser, W.L.; Weltzien, E.; Jones, J.W. Modelling Varietal Differences in Response to Phosphorus in West African Sorghum. *Eur. J. Agron.* **2018**, *100*, 35–43. [CrossRef]
23. Raymond, N.; Kopittke, P.M.; Wang, E.; Lester, D.; Bell, M.J. Does the APSIM Model Capture Soil Phosphorus Dynamics? A Case Study with Vertisols. *Field Crops Res.* **2021**, *273*, 108302. [CrossRef]
24. Hussein, M.A.; Antille, D.L.; Kodur, S.; Chen, G.; Tullberg, J.N. Controlled Traffic Farming Effects on Productivity of Grain Sorghum, Rainfall and Fertiliser Nitrogen Use Efficiency. *J. Agric. Food Res.* **2021**, *3*, 100111. [CrossRef]
25. Keating, B.A.; Carberry, P.S.; Hammer, G.L.; Probert, M.E.; Robertson, M.J.; Holzworth, D.; Huth, N.I.; Hargreaves, J.N.G.; Meinke, H.; Hochman, Z.; et al. An Overview of APSIM, a Model Designed for Farming Systems Simulation. *Eur. J. Agron.* **2003**, *18*, 267–288. [CrossRef]
26. Wimalasiri, E.M.; Jahanshiri, E.; Chimonyo, V.G.P.; Kuruppuarachchi, N.; Suhairi, T.A.S.T.M.; Azam-Ali, S.N.; Gregory, P.J. A Framework for the Development of Hemp (*Cannabis sativa* L.) as a Crop for the Future in Tropical Environments. *Ind. Crops Prod.* **2021**, *172*, 113999. [CrossRef]
27. Wimalasiri, E.M.; Jahanshiri, E.; Suhairi, T.A.S.T.M.; Udayangani, H.; Mapa, R.B.; Karunaratne, A.S.; Vidhanarachchi, L.P.; Azam-Ali, S.N. Basic Soil Data Requirements for Process-Based Crop Models as a Basis for Crop Diversification. *Sustainability* **2020**, *12*, 7781. [CrossRef]
28. Wimalasiri, E.M.; Jahanshiri, E.; Chimonyo, V.; Azam-Ali, S.N.; Gregory, P.J. Crop Model Ideotyping for Agricultural Diversification. *MethodsX* **2021**, *8*, 101420. [CrossRef]
29. Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Shelia, V.; Wilkens, P.W.; Singh, U.; White, J.W.; Asseng, S.; Lizaso, J.I.; Moreno, L.P.; et al. The DSSAT Crop Modeling Ecosystem. In *Advances in Crop Modeling for a Sustainable Agriculture*; Boote, K., Ed.; Burleigh Dodds Science Publishing: Cambridge, UK, 2019; pp. 173–216, ISBN 978-0-429-26659-1.
30. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to Conduct a Bibliometric Analysis: An Overview and Guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
31. Van Eck, N.J.; Waltman, L. Visualizing Bibliometric Networks. In *Measuring Scholarly Impact: Methods and Practice*; Ding, Y., Rousseau, R., Wolfram, D., Eds.; Springer International Publishing: Cham, Switzerland, 2014; pp. 285–320. ISBN 978-3-319-10377-8.
32. Van Eck, N.; Waltman, L. Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef]
33. Bezak, N.; Mikoš, M.; Borrelli, P.; Alewell, C.; Alvarez, P.; Anache, J.A.A.; Baartman, J.; Ballabio, C.; Biddoccu, M.; Cerdà, A.; et al. Soil Erosion Modelling: A Bibliometric Analysis. *Environ. Res.* **2021**, *197*, 111087. [CrossRef]
34. Elsevier. How Are CiteScore Metrics Used in Scopus? Available online: https://service.elsevier.com/app/answers/detail/a_id/14880/supporthub/scopus/ (accessed on 25 January 2023).
35. Kessler, M.M. *An Experimental Communication Center for Scientific and Technical Information*; Massachusetts Institute of Technology, Lincoln Laboratory: Lexington, MA, USA, 1960.
36. Jarneving, B. Bibliographic Coupling and Its Application to Research-Front and Other Core Documents. *J. Informetr.* **2007**, *1*, 287–307. [CrossRef]
37. McLaren, C.D.; Bruner, M.W. Citation Network Analysis. *Int. Rev. Sport Exerc. Psychol.* **2022**, *15*, 179–198. [CrossRef]
38. van Eck, N.J.; Waltman, L. VOS: A New Method for Visualizing Similarities between Objects. In *Proceedings of the Advances in Data Analysis*; Decker, R., Lenz, H.-J., Eds.; Springer: Berlin/Heidelberg, Germany, 2007; pp. 299–306.

39. VOSviewer—Visualizing Scientific Landscapes. Available online: https://www.vosviewer.com// (accessed on 13 January 2023).
40. Perego, A.; Giussani, A.; Sanna, M.; Fumagalli, M.; Carozzi, M.; Brenna, S.; Acutis, M. The ARMOSA Simulation Crop Model: Overall Features, Calibration and Validation Results. *Ital. J. Agrometeorol.* **2013**, *18*, 23–38.
41. Raes, D.; Steduto, P.; Hsiao, T.C.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description. *Agron. J.* **2009**, *101*, 438–447. [CrossRef]
42. Steduto, P.; Hsiao, T.C.; Raes, D.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agron. J.* **2009**, *101*, 426–437. [CrossRef]
43. Thum, T.; Caldararu, S.; Engel, J.; Kern, M.; Pallandt, M.; Schnur, R.; Yu, L.; Zaehle, S. A New Model of the Coupled Carbon, Nitrogen, and Phosphorus Cycles in the Terrestrial Biosphere (QUINCY v1.0; Revision 1996). *Geosci. Model Dev.* **2019**, *12*, 4781–4802. [CrossRef]
44. Yu, L.; Ahrens, B.; Wutzler, T.; Schrumpf, M.; Zaehle, S. Jena Soil Model (JSM v1.0; Revision 1934): A Microbial Soil Organic Carbon Model Integrated with Nitrogen and Phosphorus Processes. *Geosci. Model Dev.* **2020**, *13*, 783–803. [CrossRef]
45. Jarvis, N.; Larsbo, M.; Lewan, E.; Garré, S. Improved Descriptions of Soil Hydrology in Crop Models: The Elephant in the Room? *Agric. Syst.* **2022**, *202*, 103477. [CrossRef]
46. Liu, H.L.; Yang, J.Y.; Drury, C.F.; Reynolds, W.D.; Tan, C.S.; Bai, Y.L.; He, P.; Jin, J.; Hoogenboom, G. Using the DSSAT-CERES-Maize Model to Simulate Crop Yield and Nitrogen Cycling in Fields under Long-Term Continuous Maize Production. *Nutr. Cycl. Agroecosyst.* **2011**, *89*, 313–328. [CrossRef]
47. Luo, Z.; Wang, E.; Fillery, I.R.P.; Macdonald, L.M.; Huth, N.; Baldock, J. Modelling Soil Carbon and Nitrogen Dynamics Using Measurable and Conceptual Soil Organic Matter Pools in APSIM. *Agric. Ecosyst. Environ.* **2014**, *186*, 94–104. [CrossRef]
48. Salmerón, M.; Cavero, J.; Isla, R.; Porter, C.H.; Jones, J.W.; Boote, K.J. DSSAT Nitrogen Cycle Simulation of Cover Crop–Maize Rotations under Irrigated Mediterranean Conditions. *Agron. J.* **2014**, *106*, 1283–1296. [CrossRef]
49. Tahir, N.; Li, J.; Ma, Y.; Ullah, A.; Zhu, P.; Peng, C.; Hussain, B.; Danish, S. 20 Years Nitrogen Dynamics Study by Using APSIM Nitrogen Model Simulation for Sustainable Management in Jilin China. *Sci. Rep.* **2021**, *11*, 17505. [CrossRef] [PubMed]
50. Vogeler, I.; Giltrap, D.; Cichota, R. Comparison of APSIM and DNDC Simulations of Nitrogen Transformations and N_2O Emissions. *Sci. Total Environ.* **2013**, *465*, 147–155. [CrossRef] [PubMed]
51. Maniquiz-Redillas, M.; Robles, M.E.; Cruz, G.; Reyes, N.J.; Kim, L.-H. First Flush Stormwater Runoff in Urban Catchments: A Bibliometric and Comprehensive Review. *Hydrology* **2022**, *9*, 63. [CrossRef]
52. Bigliardi, B.; Filippelli, S. Chapter 4—Factors Affecting the Growth of Academic Oriented Spin-Offs. In *Innovation Strategies in the Food Industry*, 2nd ed.; Galanakis, C.M., Ed.; Academic Press: New York, NY, USA, 2022; pp. 53–72, ISBN 978-0-323-85203-6.