Climate Change and Soil Dynamics: A Crop Modelling Approach

soil systems

MDPI

Article

Climate Change and Soil Dynamics: A Crop Modelling Approach

Eranga M. Wimalasiri [1,*], Deshani Sirishantha [1], U. L. Karunadhipathi [2], Asanga D. Ampitiyawatta [1], 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; asirishantha@std.agri.sab.ac.lk (D.S.)
[2] Postgraduate Institute of Agriculture, University of Peradeniya, Peradeniya 20400, Sri Lanka
[3] College of Sport, Health and Engineering, Victoria University, Melbourne, VIC 8001, Australia; nitin.muttil@vu.edu.au
[4] Institute for Sustainable Industries & Liveable Cities, Victoria University, 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; upaka.rathnayake@atu.ie
* Correspondence: eranga@agri.sab.ac.lk

Abstract: The impact of global climate change is a challenge to the sustainability of many ecosystems, including soil systems. However, the performance of soil properties under future climate was rarely assessed. Therefore, this study was carried out to evaluate selected soil processes under climate change using an agri-environmental modeling approach to Sri Lanka. The Agricultural Production Systems Simulator (APSIM) model was used to simulate soil and plant-related processes using recent past (1990–2019) and future (2041–2070) climates. Future climate data were obtained for a regional climate model (RCM) under representative concentrations pathway 4.5 scenarios. Rainfalls are going to be decreased in all the tested locations under future climate scenarios while the maximum temperature showcased rises. According to simulated results, the average yield reduction under climate change was 7.4%. The simulated nitrogen content in the storage organs of paddy declined in the locations (by 6.4–25.5%) as a reason for climate change. In general, extractable soil water relative to the permanent wilting point (total available water), infiltration, and biomass carbon lost to the atmosphere decreased while soil temperature increased in the future climate. This modeling approach provides a primary-level prediction of soil dynamics under climate change, which needs to be tested using fieldwork.

Keywords: agri-environmental modelling; APSIM; crop nutrition; food security; nutrient cycling

Citation: Wimalasiri, E.M.; Sirishantha, D.; Karunadhipathi, U.L.; Ampitiyawatta, A.D.; Muttil, N.; Rathnayake, U. Climate Change and Soil Dynamics: A Crop Modelling Approach. *Soil Syst.* **2023**, *7*, 82. https://doi.org/10.3390/soilsystems7040082

Academic Editor: Bal Ram Singh

Received: 20 June 2023
Revised: 26 August 2023
Accepted: 22 September 2023
Published: 26 September 2023

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC), in its latest communication (6th Assessment Report), reported that the global mean surface temperature has increased by 1.1 °C in the 2011–2020 period compared to 1850–1900 with an alarming rate where larger increment was observed over the land compared to the ocean [1]. The IPCC expected that the global mean surface temperature would be increased by 0.8–1.7 °C during mid-century (2041–2060) and 0.7–4.0 °C at the end of this century (2081–2100), compared to the 1995–2014 period [2]. These rapid changes in the climate have adverse consequences on agriculture and food security, water availability, the economics of the countries, transport, energy systems, health, and many other aspects [3–8], which positions mankind in danger.

Soil, a natural resource that has many environmental functions and benefits, cannot escape from the consequences of climate change [9,10]. Climate change has both direct and indirect impacts on soil systems. The changes in rainfall (amount and pattern), elevated temperatures, and increased carbon dioxide concentrations alter the hydrological and biogeochemical cycles of the earth and alter soil processes directly [9]. Climate change has indirect impacts on the soil through ecosystem functioning [9,10] and affects soil properties in various ways. For example, increased temperature accelerates soil salinity, ammonia volatilization, and loss of organic carbon and reduces cation exchange capacity. Intensive and heavy rainfall destroys soil aggregates, increases erosion, causes acidification, and leaches nutrients. Reduction of rainfall reduces water availability, increases salt content, reduces nutrition acquisition capacity, and N-fixation in legumes [11]. Therefore, using the past observed data, the impact of climate on various aspects of soil properties was assessed in different geographic regions of the world. It was reported that the soil biodiversity has been negatively impacted by the changes in climate [12,13]. Climate change has an impact on soil carbon stocks [14] and soil erosion [15]. Since a significant portion of global food and fiber needs are accomplished by soil-used agriculture, any impact on the soil has the potential to threaten global food security [11]. Therefore, soil also plays a critical role in the climate system [13].

Reduction of soil moisture due to climate change can increase the irrigation water requirement in agriculture, which leads to yield reduction, negatively impacting food production. Thus, any change to soil systems under current and future climates negatively affects the food and nutritional security and sustainability of food systems [16]. Prolonged changes in climate on soil can aggravate desertification [17]. On the other hand, mismanagement practices related to the soil, such as burning biomass and extensive tillage, can accelerate climate change. Agricultural productivity depends on soil health, which is defined by a set of measurable chemical, physical, and biological properties and associated processes [18]. Thus, any negative impact on these properties will create soil health-related issues on which agricultural productivity would be in danger.

Different methods have been used to assess the response of soil properties to climate change [19]. Thus, the impact of climate change on soil properties is assessed using environmental models and crop models [1,20]. Crop models are mathematical algorithms that are used to simulate plant growth, development, and yield using predefined environmental (climate and soil), crop management, and genetic information [21–23]. They can be used in several disciplines, including environmental and climate change research [24]. Due to its diverse range of capabilities, crop models have been used to assess various soil-related processes such as soil physical properties (water, compaction, etc.), chemical properties, nutrient dynamics, greenhouse gas emission, and soil temperature [25].

However, according to the understanding of the authors, the impact of climate change on soil systems was rarely assessed in the world and never in the context of Sri Lanka using future climate and crop models. This is highly important as the whole country is still based on agriculture. With 23 million people having rice as its staple food, Sri Lanka needs heavy attention on agricultural products. Thus, conserving the soil system is highly important. Nevertheless, the country is under serious pressure due to the changing climate. It is one of the most affected countries in the world due to ongoing climate change [1]. Therefore, the objective of this paper is to assess the performance of some of the soil physicochemical properties under future climate using an agri-environmental modeling approach in Sri Lanka. The findings of the study would create multiple research avenues for soil-crop-climate-related studies. In addition, the policymakers, including other stakeholders, can be on alert for recent changes and include the outcome of this paper in their future planning processes.

2. Materials and Methods

2.1. Study Area

This study was conducted in Sri Lanka, which is an island situated in the Indian Ocean. Being a tropical country, no severe seasonal temperature variations were observed in the country. Sri Lanka is divided into three major climate zones based on the annual rainfall: wet zone (WZ) (>2500 mm annual rainfall), dry zone (DZ) (<1750 mm annual rainfall), and intermediate zone (IZ) (1750–2500 mm annual rainfall). The country is divided into 46 agroecological zones according to the climate and altitudinal characteristics [26]. Due to the diversity of the climate in the country, soils with different physicochemical properties can be observed in Sri Lanka [27]. As was stated in the introduction, the country has a rich profile for its agricultural products with high water resources. However, the management of water resources and soil structure is not at its best due to many drawbacks in policies.

2.2. Soil Data Collection

Five locations with observed soil data were used in this study, as shown in Figure 1 (Puttalam, Katunayake, Galle, Hambantota, and Badulla). The observed soil data were obtained from the SRICANSOL project [28–31], which is the most up-to-date and comprehensive soil database in Sri Lanka. These locations were selected to cover all three climate zones of the country: WZ, DZ, and IZ. Figure 1 shows the distribution of the soil sample collected sites. All five locations contain observed bulk density (g/cm^3), pH, sand, silt, and clay content (%), organic carbon (%), cation exchange capacity (cmol(+)/kg), volumetric water content (VWC) at 0.33 bars pressure (field capacity) and 15 bars pressure (permanent wilting point) for different depths. Since the soil depth varies among locations, the depths were standardized for 6 standard depths such as 0–5, 5–15, 15–30, 30–60, 60–100, and 100–200 (in cm) using the method followed by Wimalasiri et al. [32].

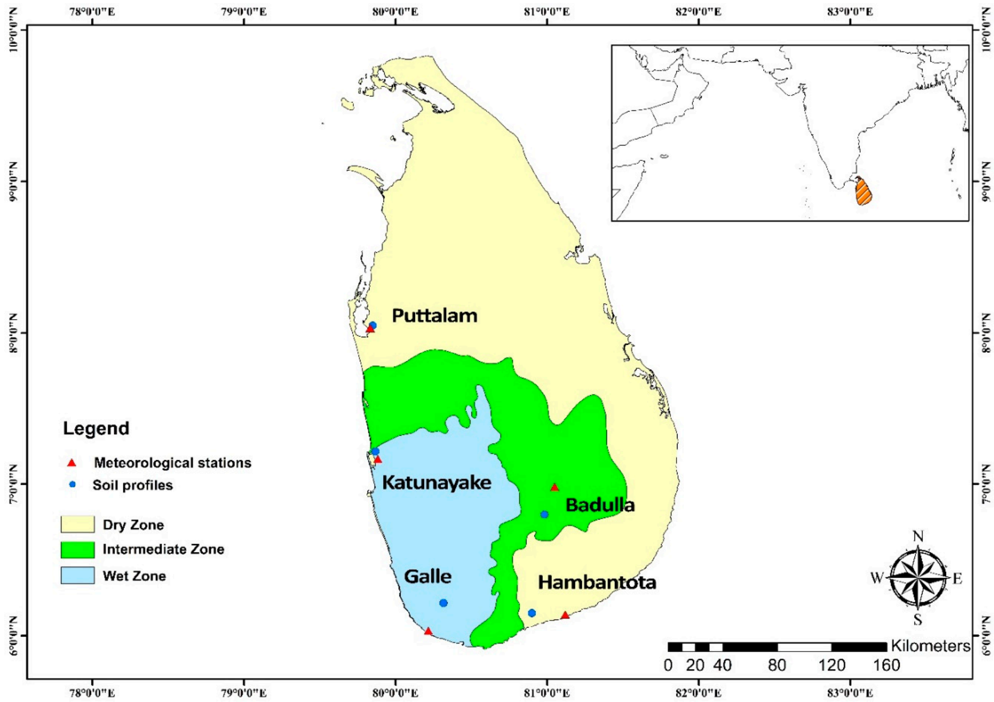


Figure 1. Distribution of soil sample collection sites and meteorological stations.

2.3. Climate Data

The closest meteorological stations to the soil sample collection sites were used (refer to Figure 1). Two types of climate data, such as recent past observed climate and future climate data, were used in this study. Observed daily rainfall and minimum and maximum temperature data for the 1990–2019 period were collected from the Department of Meteorology, Sri Lanka. Since these locations do not have solar radiation information, the data were obtained from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources NASA POWER database (https://power.larc.nasa.gov/; accessed on 1 May 2023). Daily future climate data for the 2041–2070 (mid-century) period were obtained from the Coordinated Regional Climate Downscaling Experiment (CORDEX), Copernicus Climate Change Service [33]. The regional climate model (RCM) developed for the South Asian region "RCM IITM-RegCM4-4", which is available in the database, was used under the Representative Concentration Pathway (RCP) 4.5 scenario. The horizontal resolution of the dataset is 0.44 $\times$ 0.44 degrees [33]. The grid cell that includes the meteorological station was used.

2.4. Crop Model Parameterization

Paddy (*Oryza sativa*) was used as the test crop, which is the major crop in Sri Lanka. The crop is available throughout the country, covering different agroecological zones of the country. A locally improved paddy variety BG 357 which is good for local climate conditions, was used here. The crop is usually harvested within three and half months, where it gives a potential yield of 9.5 t/ha. Even though the crop is cultivated two times per year based on the availability of water, the crop cultivated in the major season (October to March) is considered in this study. The pre-calibrated Agricultural Production Systems Simulator (APSIM) Oryza model was utilized in this study to simulate crop and soil processes [2,3]. The APSIM requires daily weather (rainfall, minimum and maximum temperatures, and solar radiation) data, soil data, and crop management information. The genetic coefficients of paddy cultivar BG 357 published by Zubair et al. [34] were used to parameterize the APSIM model. These genetic coefficients include development rate during the juvenile phase (DVRJ), development rate during the photoperiod-sensitive phase (DVRI), development rate during the panicle development phase (DVRP), development rate in the reproductive phase (DVRR), and maximum optimum photoperiod (MOPP). Then, the observed soil and climate data were used as input data, where all other management options and parameters were adjusted as described by Wimalasiri et al. [32]. The management practices include plant density and fertilizer application rates and dates.

Under both current and future climatic conditions (described in Section 2.3. Climate Data), the simulations were performed for a 30-year period separately. Different crop and soil-related parameters were simulated using the crop model. These parameters include paddy yield, nitrogen content in the storage organs of paddy plants, extractable soil water relative to permanent wilting point, infiltration, soil temperature, amount of annual nitrous oxide (N_2O) produced by denitrification and biomass carbon lost to the atmosphere. Finally, the model outputs were compared after the simulations. The overall methodology followed in this research is presented in Figure 2.

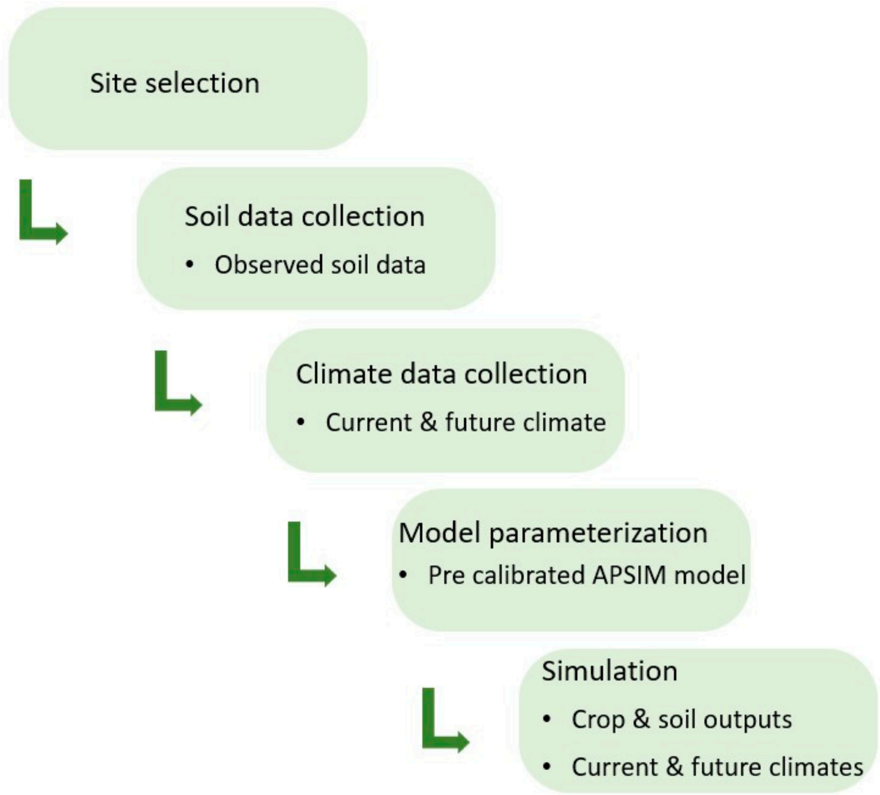


Figure 2. Flowchart of the overall methodology.

3. Results

3.1. Climate Data Analysis

Variations of current and future climates in the tested locations are shown in Figure 3. During the period considered, the highest and the lowest mean annual rainfall under the observed climates were reported from Galle (2316 ± 426.1 mm) and Hambantota (1129.7 ± 234.0), respectively. However, the mean annual rainfall in all five locations decreased as per the RCM-generated climate data. The mean annual rainfall decreased by 55.1% in Galle, followed by 53.9% in Katunayake. Both locations belong to the Wet Zone of the country. However, Hambantota showcased a lower reduction in rainfall (16.1%). The mean annual rainfall decreased by 45.1% and 25.3% in Badulla and Puttalam, respectively. However, these are based on modeled data (refer to Figure 3a). Therefore, as usual, there may be some uncertainty in the climate analysis.

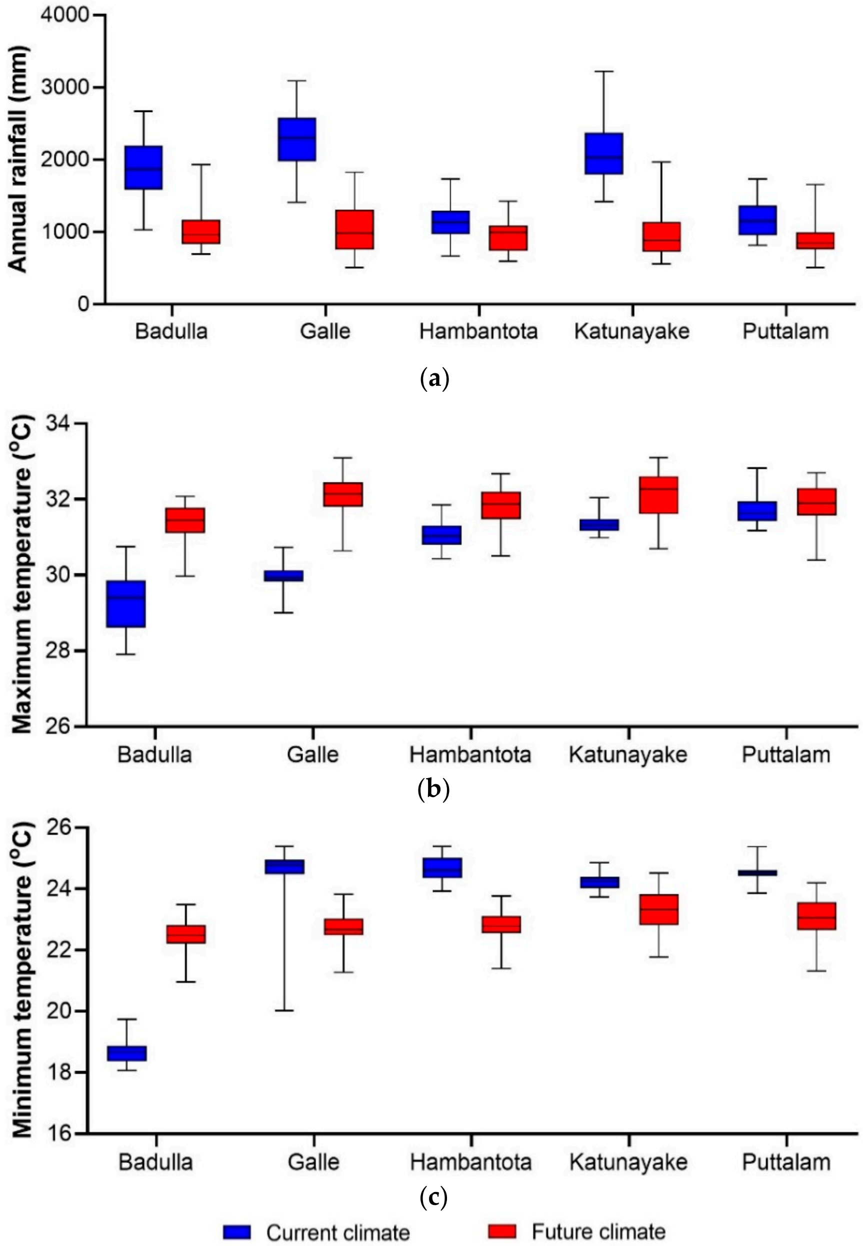


Figure 3. Comparison of the observed and future climates: (**a**) rainfall; (**b**) minimum temperature; (**c**) minimum temperature.

The mean maximum annual temperature increased in all the locations where the highest maximum temperature (refer to Figure 3b) was reported from Galle and Katunayake (32.1 °C) followed by Puttalam (31.9 °C) under future climates. The highest and the lowest increment of the maximum temperature was observed from Badulla and Galle (2.1 °C) and Puttalam (0.2 °C), respectively. In contrast, the mean annual minimum temperature (refer to Figure 3c) showed an increment in future climate only in Badulla (22.5 °C), which increased by 3.8 °C. Out of the five locations, the highest and lowest minimum temperatures were reported from Katunayake (23.6 °C) and Badulla (22.5 °C) under future climate. The mean minimum temperature decreased by 1.9 °C in Galle and Hambantota (the highest reduction) and 0.6 °C in Katunayake (the lowest reduction). The annual variation of rainfall and maximum and minimum temperatures are shown in Appendix A.

3.2. Paddy Yield Simulation Results

Simulations were carried out to develop the paddy yield from observed and forecasted climate data. Figure 4a showcases the average yields for simulated and observed scenarios from 1990 to 2019. However, it should be noted that observed average yields are for the whole area, whereas the simulated yields are for point locations based on the point data inputs. Therefore, a clear comparison of these two cannot be justified. Nevertheless, the authors have presented these two results to showcase the acceptability of the simulations. The yields are in the same range for most of the locations; thus, an acceptability of the simulated results can be seen.

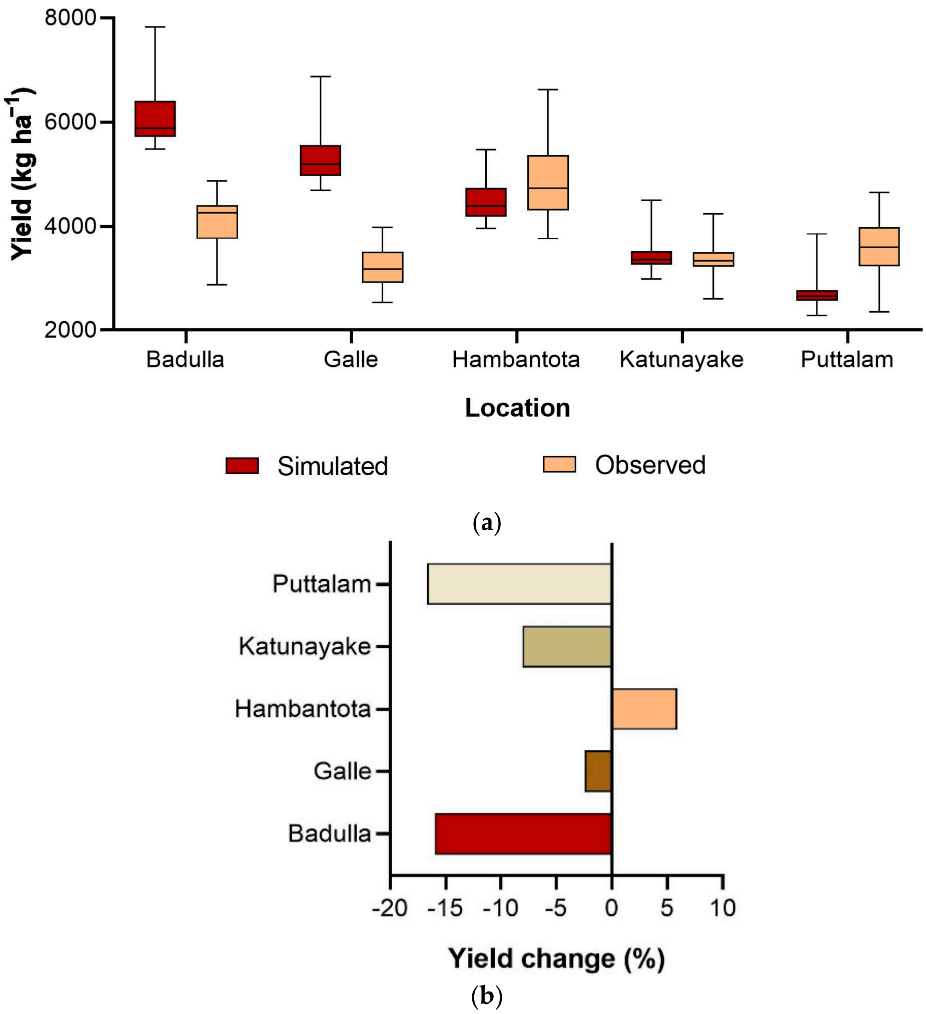
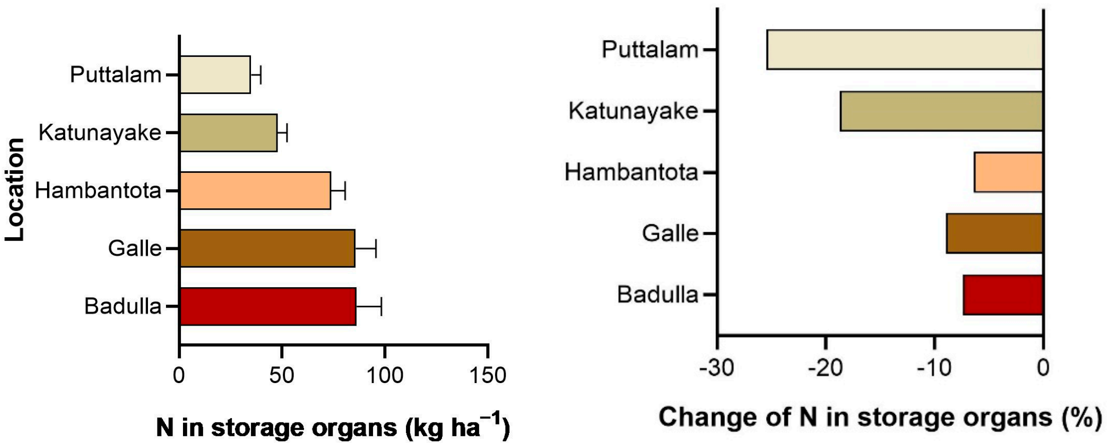


Figure 4. (**a**) Simulated vs. measured paddy yield for 1990–2019; (**b**) yield change under future climate scenario.

The simulated yields for the future scenarios (2041–2070) and their changes to simulated yields for the recent past (1990–2019) are given in Figure 4b,c. According to the simulated paddy harvest, the highest yield of 6092 ± 531 kg/ha was reported from Badulla (in the IZ), followed by Galle (5304 ± 450 kg/ha) in the WZ under the current climate. Out of the tested locations, the lowest yield of 2692 ± 280 kg/ha was reported from Puttalam. Except for Hambantota, the yields declined in other locations studied. The future paddy yields of Hambantota increased by 5.9%. The highest (5173 ± 999 kg/ha) and the lowest (2244 ± 710 kg/ha) paddy yields under the future climate were reported from Galle and Puttalam, respectively. The highest and the lowest yield reductions were reported from Puttalam (16.7%) and Galle (2.5%), respectively. Relatively higher variation was observed for paddy yield under the future climate, where the coefficient of variation (CV) was higher at 31.6% (Puttalam). The yields under both the current and future climates differed significantly ($p < 0.05$) among locations.

3.3. Plant Nutrition Related Parameters

The variation of the simulated nitrogen content in the storage organs of paddy plants under recent past climate and the change of nitrogen content in future climate scenarios are shown in Figure 5. Accordingly, the nitrogen content in the storage organs of the paddy declined in all the tested locations under the future climate, where the highest reduction of 25.5% was reported from Puttalam. Hambantota reported the lowest yield reduction of 6.4%. It should be noted that the same amount of nitrogen fertilizer was added on the same dates after sowing in both current and future climate conditions.



(**a**) (**b**)

Figure 5. (**a**) Simulated amount of nitrogen in the storage organs of paddy for 1990–2019; (**b**) change of stored nitrogen under future climate.

3.4. Soil Water Related Parameters

3.4.1. Extractable Soil Water Relative to Permanent Wilting Point (ESW)/Total Available Water

The extractable soil water relative to the permanent wilting point (ESW) decreased under the future climate scenarios in four locations except Galle, on which the value increased by 0.1% (refer to Figure 6). The highest and the lowest ESW under the current (278.8 ± 3.4 mm) and future (272.3 ± 5.5 mm) climate were reported at Badulla, where the lowest ESW under the current (187.1 ± 1.1 mm) and future (187.3 ± 0.3 mm) climates were reported at Galle. The highest reduction of the ESW under future climate was reported from Badulla (2.4%), followed by Puttalam (2.1%) and Katunayake (1.6%).

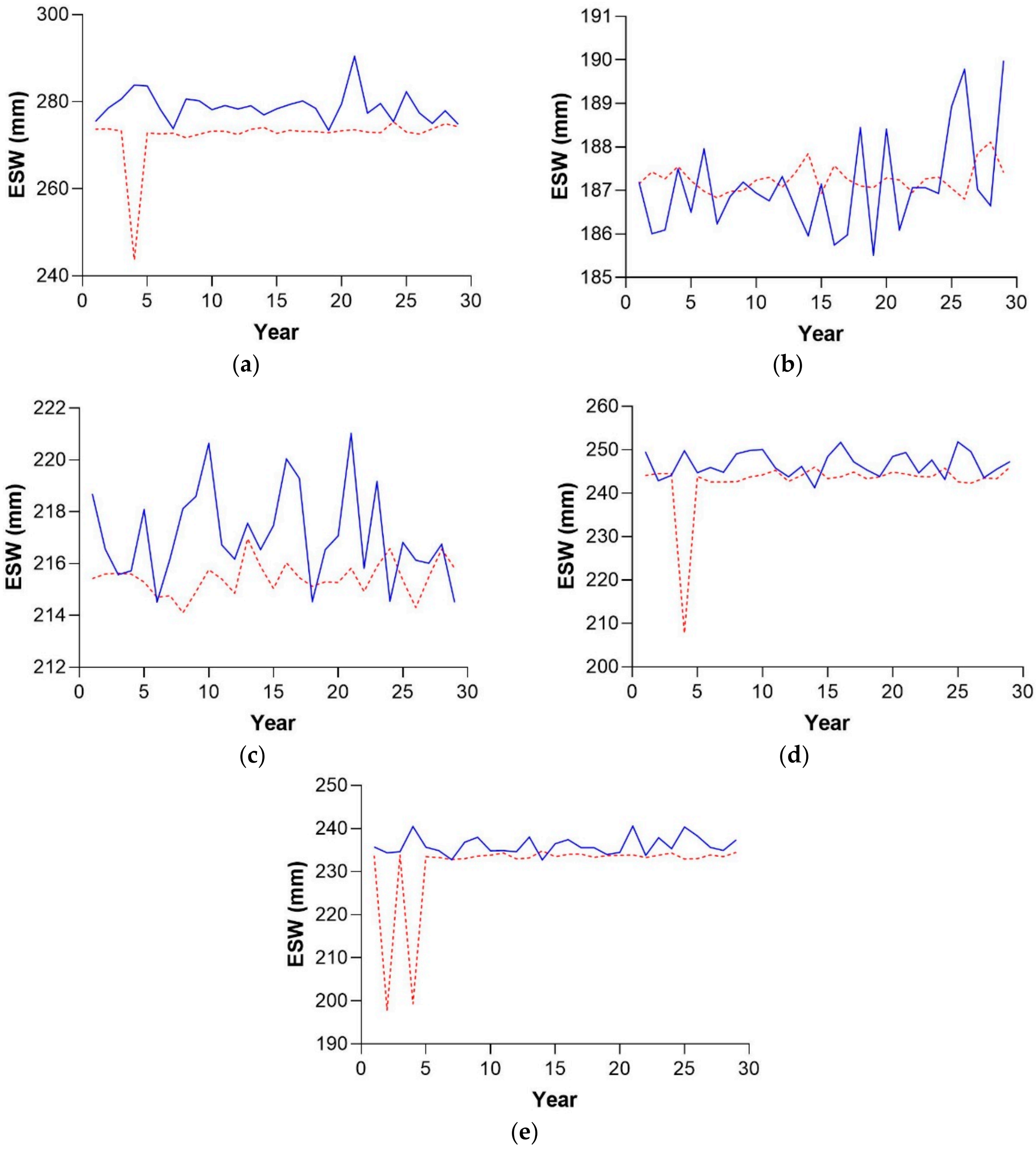


Figure 6. Variation of simulated extractable soil water content relative to permanent wilting point (total available water): (**a**) Badulla; (**b**) Galle; (**c**) Hambantota; (**d**) Katunayake; (**e**) Puttalam. 0 to 30 years indicates 1990–2019 (shown in solid lines) and 2041–2070 (shown in dotted lines) periods.

3.4.2. Infiltration

The mean annual infiltration of water in the soil decreased in all five locations under future climate conditions (refer to Figure 7). The highest annual infiltration under the recent past (6382.5 ± 219.6 mm) and future (5472.3 ± 138.9 mm) climate conditions were reported from Galle. The lowest infiltration under the current and future climate conditions was reported from Puttalam, where the values were 5496.0 ± 179.7 mm and 5238.1 ± 340.7 mm, respectively. The annual infiltration reduced from 14.3% (Galle) to 2.8% (Hambantota) under the future climate. The reductions in annual infiltration for Badulla, Katunayake, and Puttalam were 14.1%, 12.2%, and 4.7%, respectively.

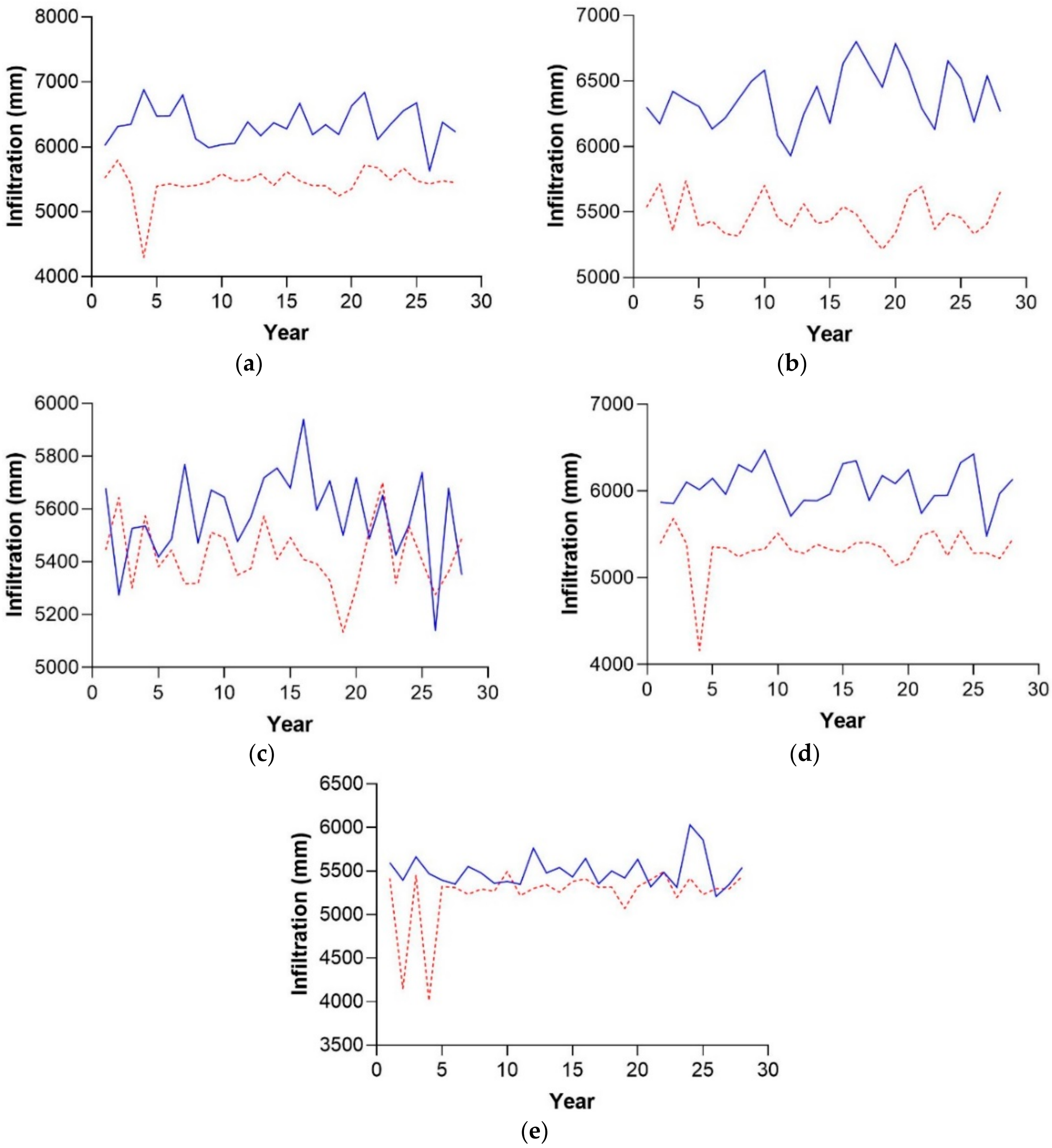


Figure 7. Variation of the simulated infiltration: (**a**) Badulla; (**b**) Galle; (**c**) Hambantota; (**d**) Katunayake; (**e**) Puttalam. 0 to 30 years indicates 1990–2019 (shown in solid lines) and 2041–2070 (shown in dotted lines) periods.

3.5. Soil Temperature

The simulations showcased both the increments and reductions of soil temperatures for future climate scenarios (refer to Figure 8). The highest and the lowest mean soil temperatures under the future climate were reported at Galle (32.3 °C) and Badulla (29.5 °C). The mean soil temperature increased by 2.1 °C in Badulla and 1.1 °C in Galle. The mean soil temperature decreased by 0.5 °C in Puttalam and 0.1 °C in Hambantota and Katunayake.

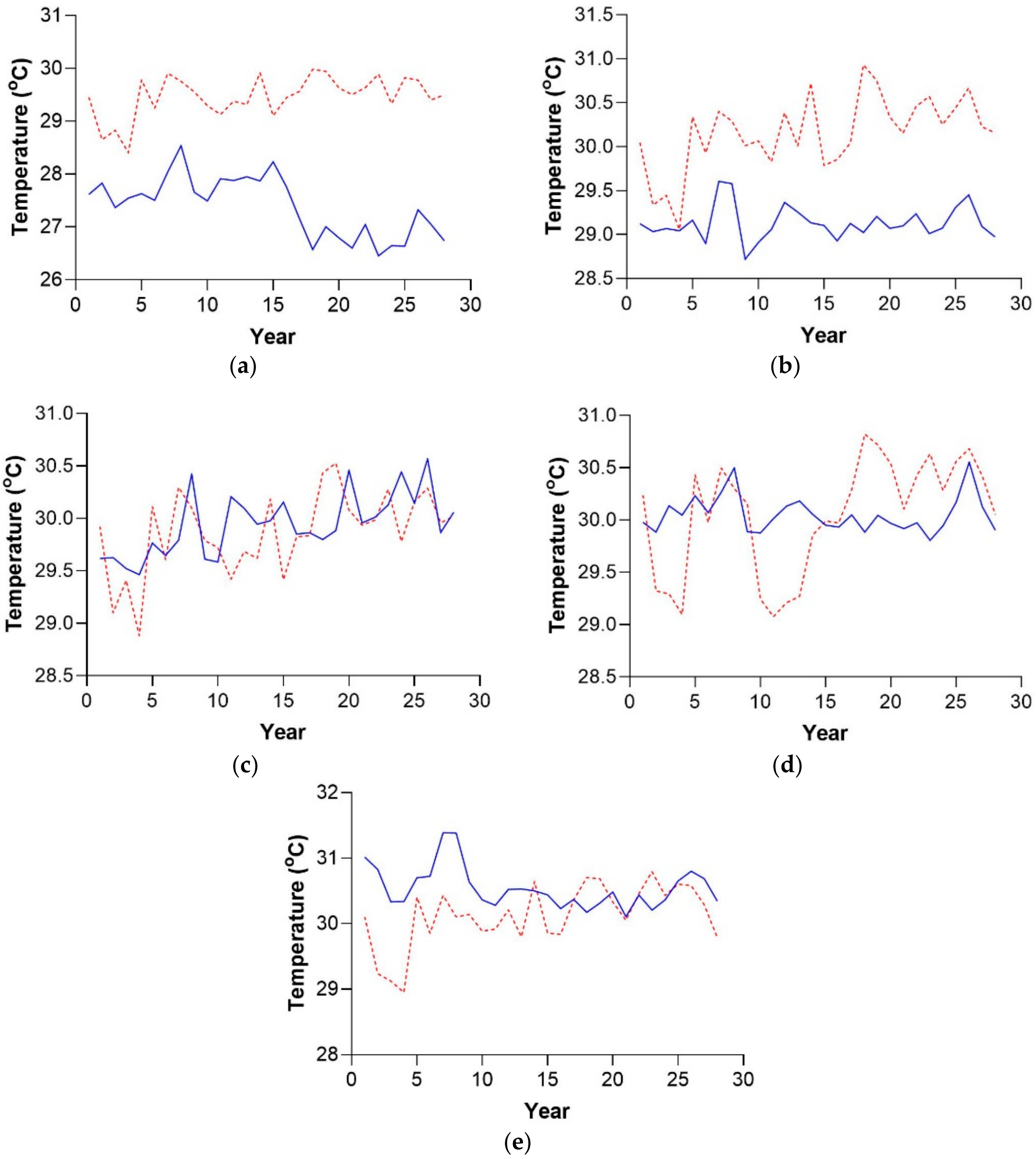
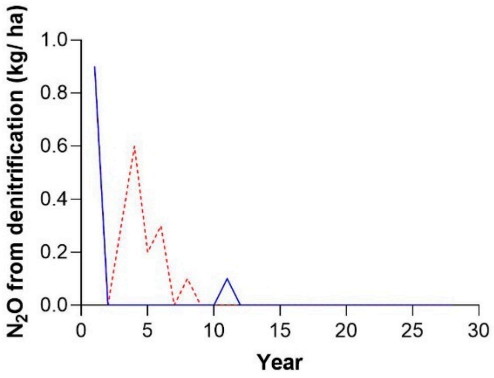


Figure 8. Variation of the simulated soil temperature: (**a**) Badulla; (**b**) Galle; (**c**) Hambantota; (**d**) Katunayake; (**e**) Puttalam. 0 to 30 years indicates 1990–2019 (shown in solid lines) and 2041–2070 (shown in dotted lines) periods.

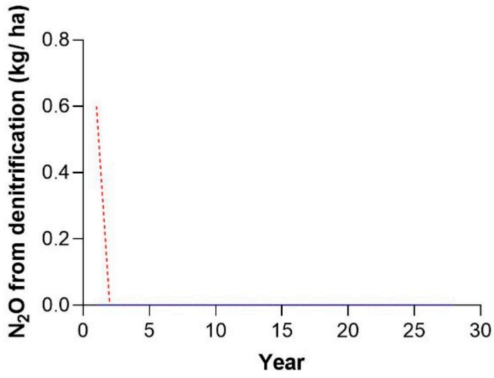
3.6. Soil Nitrogen Related Parameters

The annual nitrous oxide (N_2O) produced by denitrification was reported at three locations only: Badulla, Galle, and Hambantota (refer to Figure 9). Denitrification within the APSIM model is controlled by soil water content and flow, which is simulated from the SoilWat model. The denitrification rate within the model is calculated using the amount of NO_3^- N present, active carbon present, and moisture and temperature coefficients. Due to the variation of these properties, the denitrification can be varied. Thus, denitrification was observed for three locations only.

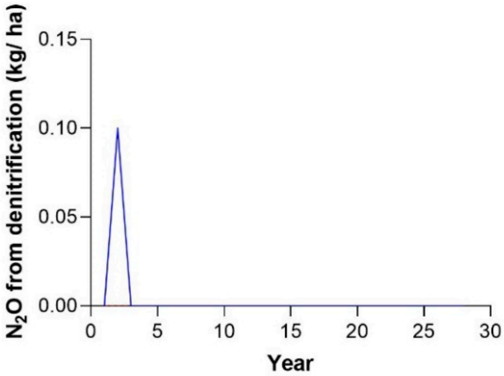
Out of three locations, the total N_2O produced by denitrification during the study period was higher in future climate in two locations: Badulla and Galle. At Badulla, the N_2O produced by denitrification was 1.0 kg/ha and 2.4 kg/ha under the current and future climates, respectively. At Galle, the N_2O was not reported under current climates, while the amount under future climates was 0.6 kg/ha. In contrast to Galle, the N_2O production was reported under current climates only, where the value was 0.1 kg/ha.



(**a**)



(**b**)

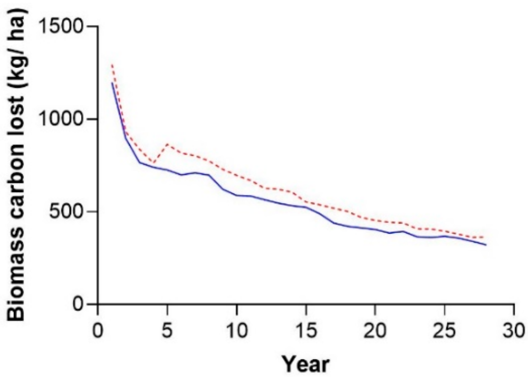


(**c**)

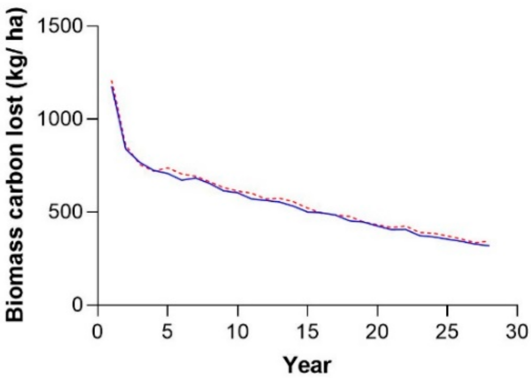
Figure 9. Variation of the simulated annual nitrous oxide (N_2O) produced by denitrification: (**a**) Badulla; (**b**) Galle; (**c**) Hambantota. 0 to 30 years indicates 1990–2019 (shown in solid lines) and 2041–2070 (shown in dotted lines) periods.

3.7. Soil Carbon Related Parameters

Finally, one of the most important parameters related to agriculture was obtained for future climate scenarios. The annual variations of biomass carbon lost to the atmosphere are shown in Figure 10. The highest mean biomass carbon loss under the current climate was observed in Badulla (552.4 ± 201.1 kg ha^{-1}), followed by Galle (549.0 ± 182.9 kg ha^{-1}). The mean annual biomass carbon lost to the atmosphere increased in all five locations. The highest increment was reported from Badulla (11.6%), followed by Hambantota (3.9%) and Galle (2.7%). The lowest increment of mean annual biomass carbon lost was reported from both Katunayake and Puttalam, where the value increased by 0.3%.

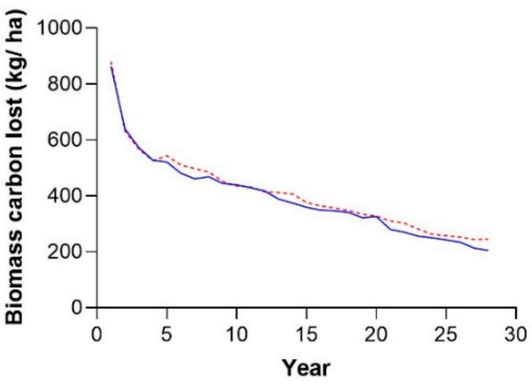


(**a**)

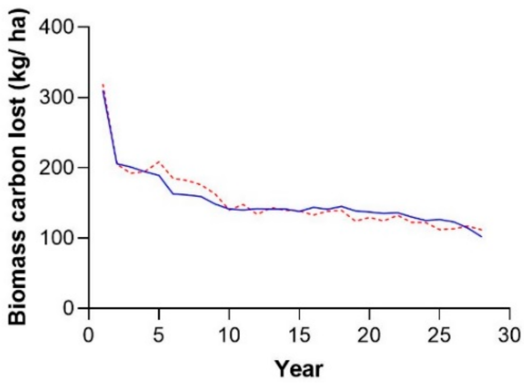


(**b**)

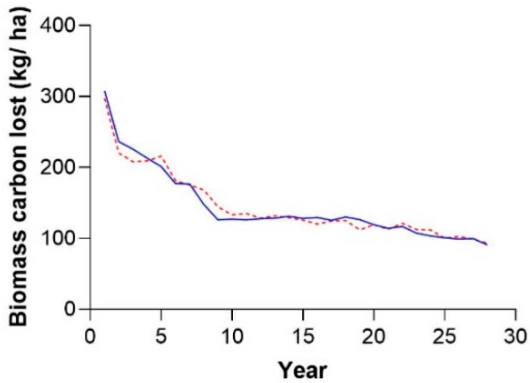
Figure 10. *Cont.*



(**c**)



(**d**)



(**e**)

Figure 10. Variation of the simulated biomass carbon lost to the atmosphere: (**a**) Badulla; (**b**) Galle; (**c**) Hambantota; (**d**) Katunayake; (**e**) Puttalam. 0 to 30 years indicates 1990–2019 (shown in solid lines) and 2041–2070 (shown in dotted lines) periods.

4. Discussion

Agri-environmental modeling approaches are important to understand the agriculture-environment-related processes, their interactions, and their effects on other systems [25,35]. Understanding the soil dynamics under future climate using modeling approaches is important in decision-making regarding the best use and conservation of soil properties. This is highly important in achieving sustainable development goals (SDGs) for the future world. Therefore, this research was carried out to investigate the soil processes for future climate scenarios, thus understanding the food security of tomorrow's world. Important results are obtained from this research and presented in the preceding section. However, these results are based on the RCM-generated climate scenarios where there is uncertainty in the future data. Nevertheless, many researchers have used these RCM-generated future climate scenarios to understand and forecast the important parameters for the future. The whole idea may not be to reach perfection for the future but to reach some understanding of what the future would be.

According to the selected RCMs, the rainfall showed a reduction in the future compared to the current climate. However, both the increment and reduction of rainfall under future climates were reported in Sri Lanka [36–38]. Since rainfall determines the soil water availability and related processes within the soil system in countries such as Sri Lanka, this needs to be validated using future climate models to obtain efficient model outputs related to soil. Soil water availability determines most of the chemical properties of soil. Agricultural soils receive water by either irrigation or rainfall. Since the rainfall amount under the future climate is lower compared to the recent past climate, the natural water supply to agricultural soils is lower, which can hinder some of the processes in the soil. This is evident from the fact that infiltration of water under future climate scenarios is lower in all the locations compared to the recent past climate. Since the availability of soil water is one of the major constraints under future climate, management practices that retain water are important. Some soil amendments, such as biochar, can be used in this regard [39]. According to the study, soil evaporation decreased in all the tested locations under future climate. In APSIM, evaporation is calculated in two stages based on the potential evaporation determined using the Priestley–Taylor method [40]. Thus, surface energy flux, atmospheric pressure, and surface air temperature determine the values [41].

Compared to other parameters assessed, soil temperature showed both increment and reduction irrespective of the location or the climate zone. To simulate soil temperature, APSIM uses air temperature from the input file, water from the soil water module, and evaporation and incident net radiation [42]. Soil temperatures have a great effect on plant growth by influencing nutrient and water uptake, root growth, and other physiological processes of plants [43,44]. Increased temperature and reduction of moisture as a reason for declined rainfall influence the biological transformation between inorganic and organic pools in the soil [11]. Elevated temperature and carbon dioxide concentration affect the soil microbial activity and nutrient cycling in the soil [11,45,46]. Since soil microbes are sensitive to temperature, increased temperature increases their activity and respiration, releasing nitrogen and phosphorus from organic matter in bioavailable forms [11,45]. Moreover, it decreases both the quality and the quantity of organic matter in the soil [45], which negatively affects the soil-plant interactions. Increased microbial activity can be suggested as the reason for increased atmospheric carbon loss. Through the carbon cycle–climate feedback, soil microbial activity contributes to climate change, triggering human-induced climate changes [47]. Therefore, it is important to improve soil carbon sequestration to mitigate climate change [48].

5. Conclusions and Recommendations

This study was carried out for the first time in Sri Lanka to understand the soil processes under changing climates. The consequences of global climate change are expected to impact the soil's physical, chemical, and biological properties worldwide. Nevertheless, such studies have not been paid enough attention by many researchers, leading to poor directions to policymakers. Therefore, this initiative would open up the possibility of enhancing more research along these lines and achieving food security for future generations under the SDGs.

This modeling approach showed that soil evaporation, extractable soil water relative to a permanent wilting point, infiltration, soil temperature, annual nitrous oxide produced by denitrification, and biomass carbon lost to the atmosphere changed under future climate in different magnitudes. The reduced future rainfall that limits available soil water will cause a threat to agriculture. It is important to take measures to conserve soil moisture and sequestration of carbon in the soil. The initial level data generated using the modeling approach should be validated using field experiments before use in decision-making.

Even though there are several other soil parameters, few physicochemical properties were assessed in this study. As a reason for the uncertainty of climate models, varied results for the same outputs can be expected under the same climate [36,49]. Different models perform in different ways to model structural uncertainty [22,50]. Therefore, we expected to conduct the study using several future climate scenarios, environmental models, and soil properties. Therefore, a comparative analysis is proposed to understand the model with different climatic scenarios comprehensively. In addition, in process-based crop models such as APSIM, different processes are governed by different biophysical models or modules [22,51]. For example, soil water processes in the model are governed by the SoilWat model [52,53]. The inputs, outputs, and capabilities of such models depend on several factors. Therefore, the model output should be validated before use in decision-making.

Author Contributions: Conceptualization, E.M.W.; methodology, E.M.W., D.S. and U.L.K.; software, E.M.W. and D.S.; validation, E.M.W. and D.S.; formal analysis, E.M.W., D.S. and U.L.K.; writing—original draft preparation, E.M.W., D.S., A.D.A. and U.L.K.; writing—review and editing, U.R. and

N.M.; visualization, E.M.W. and D.S.; project administration, E.M.W. and U.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The dataset is available from research work by the corresponding author.

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

Appendix A

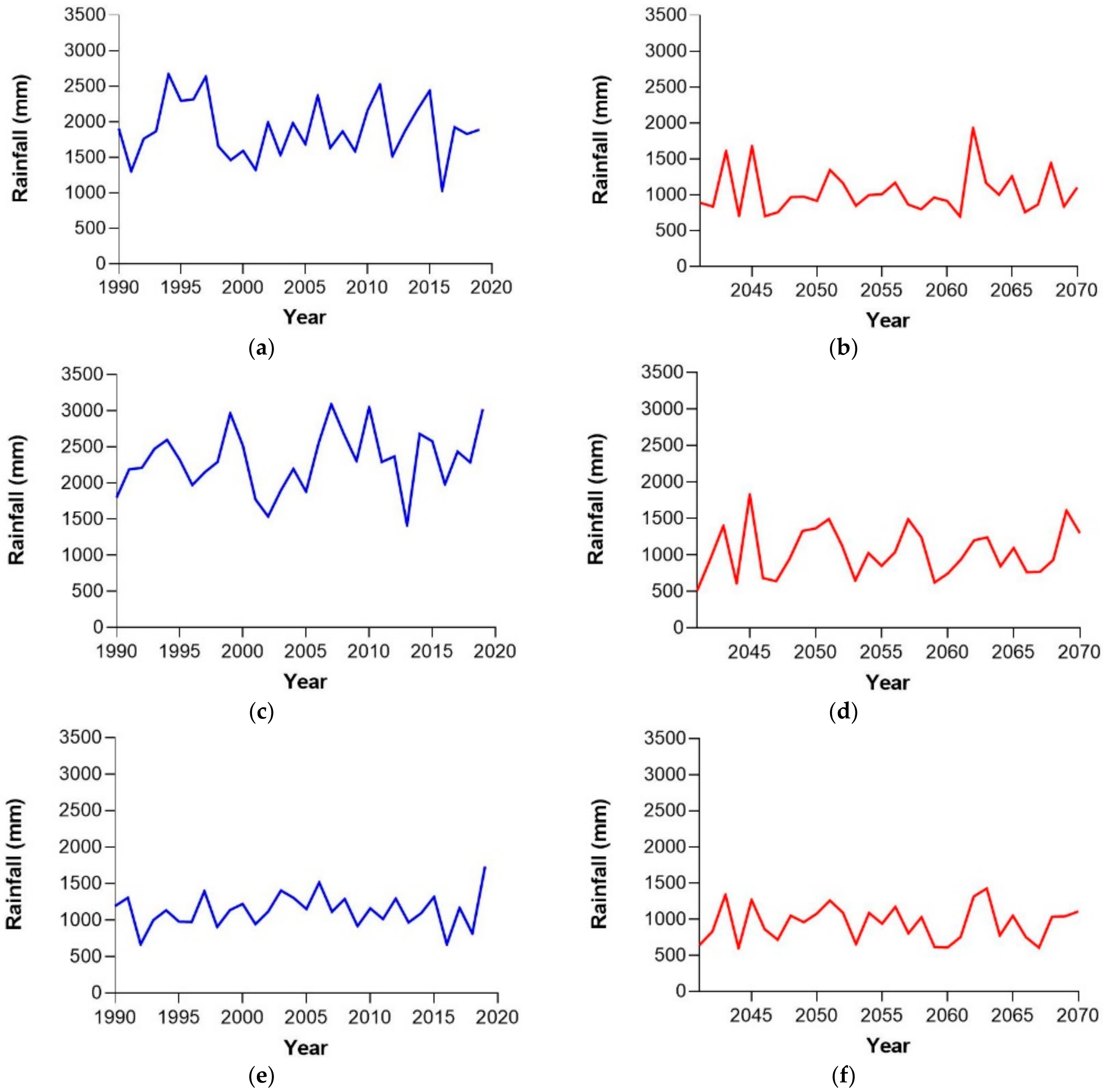


Figure A1. *Cont.*

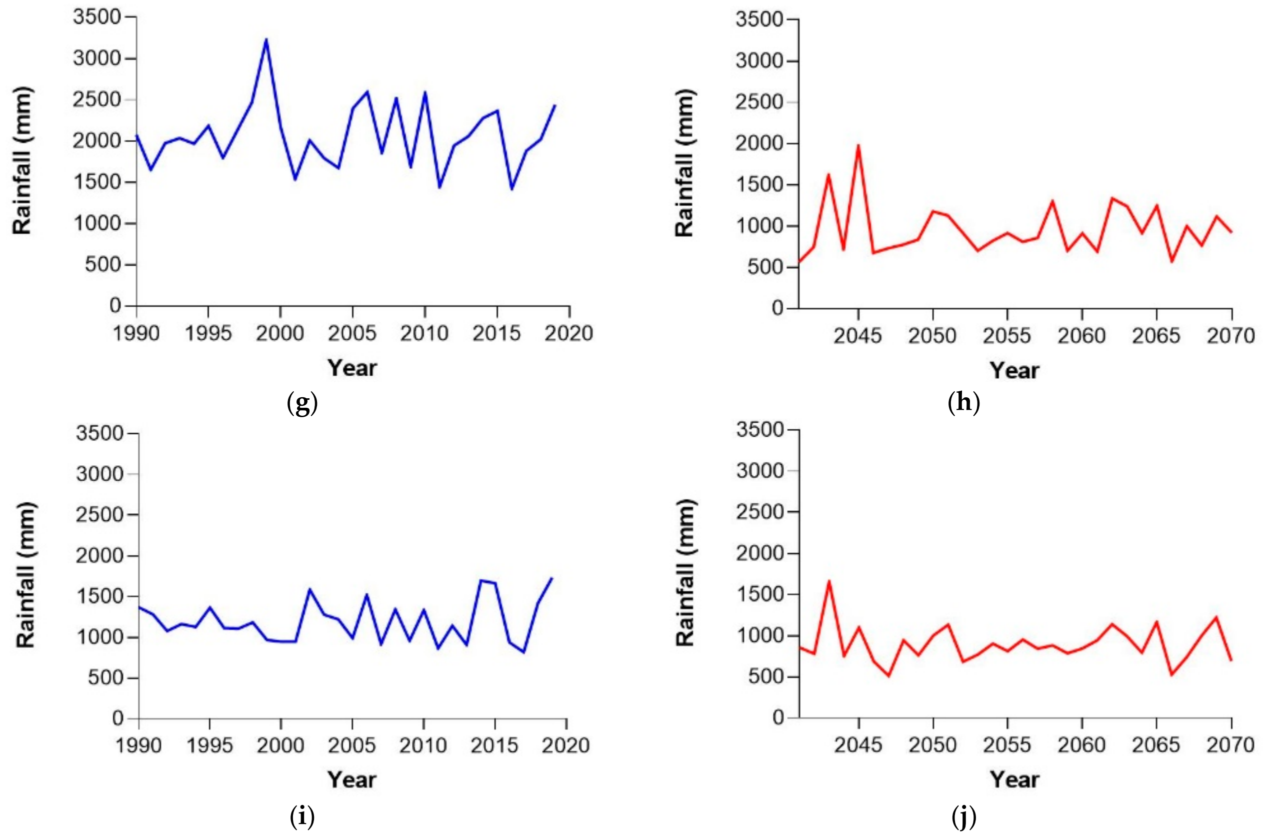


Figure A1. Variation of rainfall for recent past and future climates: (**a**,**b**) Badulla, (**c**,**d**) Galle; (**e**,**f**) Hambantota; (**g**,**h**) Katunayake; (**i**,**j**) Puttalam. (Straight lines were used only to showcase the variation and no connectivity of annual rainfalls to each other).

References

1. Valkama, E.; Kunypiyaeva, G.; Zhapayev, R.; Karabayev, M.; Zhusupbekov, E.; Perego, A.; Schillaci, C.; Sacco, D.; Moretti, B.; Grignani, C.; et al. Can Conservation Agriculture Increase Soil Carbon Sequestration? A Modelling Approach. *Geoderma* **2020**, *369*, 114298. [CrossRef]
2. Bouman, B.A.M.; van Laar, H.H. Description and Evaluation of the Rice Growth Model ORYZA2000 under Nitrogen-Limited Conditions. *Agric. Syst.* **2006**, *87*, 249–273. [CrossRef]
3. Gaydon, D.S.; Probert, M.E.; Buresh, R.J.; Meinke, H.; Suriadi, A.; Dobermann, A.; Bouman, B.; Timsina, J. Rice in Cropping Systems—Modelling Transitions between Flooded and Non-Flooded Soil Environments. *Eur. J. Agron.* **2012**, *39*, 9–24. [CrossRef]
4. Lee, H.; Romero, J. (Eds.) IPCC Summary for Policymakers. In *Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2023; p. 36.
5. Lee, J.Y.; Marotzke, J.; Bala, G.; Cao, L.; Corti, S.; Dunne, J.P.; Engelbrecht, F.; Fischer, E.; Fyfe, J.C.; Jones, C.; et al. Future Global Climate: Scenario-Based Projections and Near-Term Information. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021; pp. 553–672.
6. Anh, D.L.T.; Anh, N.T.; Chandio, A.A. Climate Change and Its Impacts on Vietnam Agriculture: A Macroeconomic Perspective. *Ecol. Inform.* **2023**, *74*, 101960. [CrossRef]
7. Anik, A.H.; Sultan, M.B.; Alam, M.; Parvin, F.; Ali, M.M.; Tareq, S.M. The Impact of Climate Change on Water Resources and Associated Health Risks in Bangladesh: A Review. *Water Secur.* **2023**, *18*, 100133. [CrossRef]
8. Koetse, M.J.; Rietveld, P. The Impact of Climate Change and Weather on Transport: An Overview of Empirical Findings. *Transp. Res. Part D Transp. Environ.* **2009**, *14*, 205–221. [CrossRef]
9. Malhi, G.S.; Kaur, M.; Kaushik, P. Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review. *Sustainability* **2021**, *13*, 1318. [CrossRef]
10. Nikolaou, G.; Neocleous, D.; Christou, A.; Kitta, E.; Katsoulas, N. Implementing Sustainable Irrigation in Water-Scarce Regions under the Impact of Climate Change. *Agronomy* **2020**, *10*, 1120. [CrossRef]

11. Perera, A.T.D.; Nik, V.M.; Chen, D.; Scartezzini, J.-L.; Hong, T. Quantifying the Impacts of Climate Change and Extreme Climate Events on Energy Systems. *Nat. Energy* **2020**, *5*, 150–159. [CrossRef]
12. Gelybó, G.; Tóth, E.; Farkas, C.; Horel, Á.; Kása, I.; Bakacsi, Z. Potential Impacts of Climate Change on Soil Properties. *Agrokémia És Talajt.* **2018**, *67*, 121–141. [CrossRef]
13. Hamidov, A.; Helming, K.; Bellocchi, G.; Bojar, W.; Dalgaard, T.; Ghaley, B.B.; Hoffmann, C.; Holman, I.; Holzkämper, A.; Krzeminska, D.; et al. Impacts of Climate Change Adaptation Options on Soil Functions: A Review of European Case-studies. *Land. Degrad. Dev.* **2018**, *29*, 2378–2389. [CrossRef] [PubMed]
14. Mondal, S. Impact of Climate Change on Soil Fertility. In *Climate Change and the Microbiome: Sustenance of the Ecosphere*; Choudhary, D.K., Mishra, A., Varma, A., Eds.; Soil Biology; Springer International Publishing: Cham, Switzerland, 2021; pp. 551–569, ISBN 978-3-030-76863-8.
15. Jansson, J.K.; Hofmockel, K.S. Soil Microbiomes and Climate Change. *Nat. Rev. Microbiol.* **2020**, *18*, 35–46. [CrossRef] [PubMed]
16. Leal Filho, W.; Nagy, G.J.; Setti, A.F.F.; Sharifi, A.; Donkor, F.K.; Batista, K.; Djekic, I. Handling the Impacts of Climate Change on Soil Biodiversity. *Sci. Total Environ.* **2023**, *869*, 161671. [CrossRef] [PubMed]
17. Jones, C.; McConnell, C.; Coleman, K.; Cox, P.; Falloon, P.; Jenkinson, D.; Powlson, D. Global Climate Change and Soil Carbon Stocks; Predictions from Two Contrasting Models for the Turnover of Organic Carbon in Soil. *Glob. Change Biol.* **2005**, *11*, 154–166. [CrossRef]
18. Borrelli, P.; Robinson, D.A.; Panagos, P.; Lugato, E.; Yang, J.E.; Alewell, C.; Wuepper, D.; Montanarella, L.; Ballabio, C. Land Use and Climate Change Impacts on Global Soil Erosion by Water (2015–2070). *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 21994–22001. [CrossRef] [PubMed]
19. Brevik, E.C. The Potential Impact of Climate Change on Soil Properties and Processes and Corresponding Influence on Food Security. *Agriculture* **2013**, *3*, 398–417. [CrossRef]
20. Zhang, C.; Wang, X.; Li, J.; Hua, T. Identifying the Effect of Climate Change on Desertification in Northern China via Trend Analysis of Potential Evapotranspiration and Precipitation. *Ecol. Indic.* **2020**, *112*, 106141. [CrossRef]
21. Jat, M.L.; Stirling, C.M.; Jat, H.S.; Tetarwal, J.P.; Jat, R.K.; Singh, R.; Lopez-Ridaura, S.; Shirsath, P.B. Chapter Four—Soil Processes and Wheat Cropping Under Emerging Climate Change Scenarios in South Asia. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2018; Volume 148, pp. 111–171.
22. Emmett, B.A.; Beier, C.; Estiarte, M.; Tietema, A.; Kristensen, H.L.; Williams, D.; Peñuelas, J.; Schmidt, I.; Sowerby, A. The Response of Soil Processes to Climate Change: Results from Manipulation Studies of Shrublands Across an Environmental Gradient. *Ecosystems* **2004**, *7*, 625–637. [CrossRef]
23. Wan, Y.; Lin, E.; Xiong, W.; Li, Y.; Guo, L. Modeling the Impact of Climate Change on Soil Organic Carbon Stock in Upland Soils in the 21st Century in China. Agriculture. *Ecosyst. Environ.* **2011**, *141*, 23–31. [CrossRef]
24. 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.
25. Holzworth, D.P.; Huth, N.I.; de Voil, 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]
26. Jones, J.W.; Antle, J.M.; Basso, B.; Boote, K.J.; Conant, R.T.; Foster, I.; Godfray, H.C.J.; Herrero, M.; Howitt, R.E.; Janssen, S.; et al. Brief History of Agricultural Systems Modeling. *Agric. Syst.* **2017**, *155*, 240–254. [CrossRef] [PubMed]
27. 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] [PubMed]
28. Wimalasiri, E.M.; Ariyachandra, S.; Jayawardhana, A.; Dharmasekara, T.; Jahanshiri, E.; Muttil, N.; Rathnayake, U. Process-Based Crop Models in Soil Research: A Bibliometric Analysis. *Soil. Syst.* **2023**, *7*, 43. [CrossRef]
29. Punyawardena, B.V.R. *Precipitation of Sri Lanka and Agro-Ecological Regions*; Agriculture Press: Peradeniya, Sri Lanka, 2008.
30. Mapa, R.B. Soil Research and Soil Mapping History. In *The Soils of Sri Lanka*; Mapa, R.B., Ed.; World Soils Book Series; Springer International Publishing: Cham, Switzerland, 2020; pp. 1–11, ISBN 978-3-030-44144-9.
31. Mapa, R.B.; Somasiri, S.; Magarajah, S. *Soils of the Wet Zone of Sri Lanka: Morphology, Characterization and Classification*; Special Publication No. 1; Soil Science Society of Sri Lanka, Sarvodaya Wishva Lekha: Colombo, Sri Lanka, 1999.
32. Mapa, R.B.; Dassanayake, A.R.; Nayakekorale, H.B. *Soils of the Intermediate Zone of Sri Lanka: Morphology, Characterization and Classification*; Special Publication No. 4; Soil Science Society of Sri Lanka, Sarvodaya Wishva Lekha: Colombo, Sri Lanka, 2005.
33. Mapa, R.B.; Somasiri, S.; Dassanayake, A.R. *Soils of the Dry Zone of Sri Lanka: Morphology, Characterization and Classification*; Special Publication No. 7; Soil Science Society of Sri Lanka, Sarvodaya Wishva Lekha: Colombo, Sri Lanka, 2010.
34. Mapa, R.B. *Characterization of Soils in the Northern Region of Sri Lanka to Develop a Soil Data Base for Land Use Planning and Environmental Applications*; National Research Council of Sri Lanka: Colombo, Sri Lanka, 2016.
35. 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]
36. Copernicus Climate Change Service CORDEX Regional Climate Model Data on Single Levels. Copernicus Climate Change Service (C3S) Climate Data Store (CDS) 2019. Available online: https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.bc91edc3?tab=overview (accessed on 26 May 2023).

37. Zubair, L.; Nissanka, S.P.; Weerakoon, W.M.W.; Herath, D.I.; Karunaratne, A.S.; Prabodha, A.S.M.; Agalawatte, M.B.; Herath, R.M.; Yahiya, S.Z.; Punyawardhene, B.V.R. Climate Change Impacts on Rice Farming Systems in Northwestern Sri Lanka. In *Series on Climate Change Impacts, Adaptation, and Mitigation*; Imperial College Press: London, UK, 2015; Volume 4, pp. 315–352, ISBN 978-1-78326-563-3.
38. van Ittersum, M.; Brouwer, F. Introduction. In *Environmental and Agricultural Modelling: Integrated Approaches for Policy Impact Assessment*; Brouwer, F.M., Ittersum, M.K., Eds.; Springer: Dordrecht, The Netherlands, 2010; pp. 1–7, ISBN 978-90-481-3619-3.
39. 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]
40. Selvarajah, H.; Koike, T.; Rasmy, M.; Tamakawa, K.; Yamamoto, A.; Kitsuregawa, M.; Zhou, L. Development of an Integrated Approach for the Assessment of Climate Change Impacts on the Hydro-Meteorological Characteristics of the Mahaweli River Basin, Sri Lanka. *Water* **2021**, *13*, 1218. [CrossRef]
41. Chathuranika, I.M.; Gunathilake, M.B.; Azamathulla, H.M.; Rathnayake, U. Evaluation of Future Streamflow in the Upper Part of the Nilwala River Basin (Sri Lanka) under Climate Change. *Hydrology* **2022**, *9*, 48. [CrossRef]
42. Razzaghi, F.; Obour, P.B.; Arthur, E. Does Biochar Improve Soil Water Retention? A Systematic Review and Meta-Analysis. *Geoderma* **2020**, *361*, 114055. [CrossRef]
43. Priestley, C.H.B.; Taylor, R.J. On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. *Mon. Weather. Rev.* **1972**, *100*, 81–92. [CrossRef]
44. Gan, G.; Liu, Y.; Pan, X.; Zhao, X.; Li, M.; Wang, S. Seasonal and Diurnal Variations in the Priestley–Taylor Coefficient for a Large Ephemeral Lake. *Water* **2020**, *12*, 849. [CrossRef]
45. APSIM Soil Modules Documentation. Available online: https://www.apsim.info/documentation/model-documentation/soil-modules-documentation/ (accessed on 2 June 2023).
46. Onwuka, B. Effects of Soil Temperature on Some Soil Properties and Plant Growth. *APAR* **2018**, *8*, 34–37. [CrossRef]
47. Göbel, L.; Coners, H.; Hertel, D.; Willinghöfer, S.; Leuschner, C. The Role of Low Soil Temperature for Photosynthesis and Stomatal Conductance of Three Graminoids From Different Elevations. *Front. Plant Sci.* **2019**, *10*, 330. [CrossRef] [PubMed]
48. Ruan, Y.; Kuzyakov, Y.; Liu, X.; Zhang, X.; Xu, Q.; Guo, J.; Guo, S.; Shen, Q.; Yang, Y.; Ling, N. Elevated Temperature and CO_2 Strongly Affect the Growth Strategies of Soil Bacteria. *Nat. Commun.* **2023**, *14*, 391. [CrossRef] [PubMed]
49. Sünnemann, M.; Siebert, J.; Reitz, T.; Schädler, M.; Yin, R.; Eisenhauer, N. Combined Effects of Land-Use Type and Climate Change on Soil Microbial Activity and Invertebrate Decomposer Activity. *Agric. Ecosyst. Environ.* **2021**, *318*, 107490. [CrossRef]
50. Bardgett, R.D.; Freeman, C.; Ostle, N.J. Microbial Contributions to Climate Change through Carbon Cycle Feedbacks. *ISME J.* **2008**, *2*, 805–814. [CrossRef]
51. Lal, R. Soil Carbon Sequestration to Mitigate Climate Change. *Geoderma* **2004**, *123*, 1–22. [CrossRef]
52. Probert, M.E.; Dimes, J.P.; Keating, B.A.; Dalal, R.C.; Strong, W.M. APSIM's Water and Nitrogen Modules and Simulation of the Dynamics of Water and Nitrogen in Fallow Systems. *Agric. Syst.* **1998**, *56*, 1–28. [CrossRef]
53. Verburg, K.; Bond, W.J. *Use of APSIM to Simulate Water Balances of Dryland Farming Systems in South Eastern Australia*; CSIRO Land and Water: Canberra, Australia, 2003.