Agronomy Research **23**(X), xxx–ccc, 2025

Evaluating the STICS Soil-Crop Model on durum wheat-chickpea intercropping system under the semi-arid conditions of Southern Tunisia

A. Attallah[1], W. Hamdi[1,*], K. Van den Meersche[2], A. Souid[1], D.E. Kucher [3], O.A. Zakharova[4], M. Farissi[5], B. L' taief[6], J.A. Messiga[7], S. Jellali[8] and N.Y. Rebouh[3]

[1]Gabes University, Higher Institute of the Sciences and Techniques of Waters of Gabes, Zrig, 6072 Gabès, Tunisia
[2]Eco&Sols, Univ Montpellier, CIRAD, INRAE, Institut Agro, IRD, 2 place Pierre Viala, 34060 Montpellier, France
[3]Department of Environmental Management, Institute of Environmental Engineering, RUDN University, 6 Miklukho-Maklaya Str., RU117198 Moscow, Russia
[4]Department of agronomy and agrotechnologies, Ryazan State Agrotechnological University Named after P.A. Kostychev, 1, Kostychev Str., RU390044 Ryazan Russia
[5]Laboratory of Biotechnology & Sustainable Development of Natural Resources, Polydisciplinary Faculty of Beni-Mellal, Sultan Moulay Slimane University, Beni-Mellal 23000, Morocco
[6]Biology Department, College of Science, King Khalid University, P.O. Box 960, 62223 Abha, Saudi Arabia
[7]Agassiz Research and Development Centre, Agriculture and Agri-Food Canada, Agassiz, BC V0M1A0, Canada
[8]Center for Environmental Studies and Research, Sultan Qaboos University, Al-Khoud 123, Muscat, Oman
[*]Correspondence: wissemhemdi@yahoo.fr

Received: March 12th, 2025; Accepted: July 4th, 2025; Published: September 2nd, 2025

Abstract. Soil-crop models provide critical insights for designing and assessing innovative cropping systems, particularly for improving sustainability in water-limited regions. However, accurately modeling intercropping systems particularly those involving grains and legumes continues to pose a significant challenge in agricultural research. This study focuses on the initial calibration and evaluation of the STICS soil-crop model for a durum wheat-chickpea intercropping system in Mediterranean semi-arid conditions. Field experiments were conducted during 2020–2021 and 2021–2022 cropping seasons in the Medenine region, Tunisia, with comparison between the intercropping and monoculture systems. The Model performance was evaluated using Aboveground Plant Nitrogen (AGPN) as an indicator of nitrogen uptake. The STICS model demonstrated satisfactory predictive capacity across most simulations, with efficiency (EFF) values ranging from 0.56 to 0.80. Grain yield predictions were reasonably accurate, as indicated by a normalized root mean square error (NRMSE) of $\leq$ 37%, particularly for durum wheat (EFF $\geq$ 0.55). The model effectively simulated the soil water content, achieving an efficiency (EFF) of ≥ 0.51 and an NRMSE of ≤ 25%, especially in the chickpea plots. However, the predictions of the soil nitrogen stock were less accurate in the chickpea monocultures, with efficiency values ≤ 0.38 and NRMSE ≥ 44%. The intercropping simulations showed moderate accuracy, with efficiency values up to 0.41. These findings highlight the potential complementary interactions between durum wheat and chickpeas in using nitrogen and carbon resources. This study contributes to the development of sustainable agricultural practices tailored to Mediterranean climates, supporting climate adaptation and resource efficiency.

Key words: carbon, crop modeling, grain yield, nitrogen, soil water content, sustainable agriculture.

INTRODUCTION

Agricultural practices in semi-arid and arid regions are likely to face numerous challenges, mainly due to the combined effect of climate change, which exacerbates the problems of water availability and land degradation (IPCC, 2019; FAO, 2020). The rising climatic variability has challenged global food productions systems i.e., grasslands, fields crops, fruit crops and livestock (Rafique et al., 2021; Rafique et al., 2023). It has also altered crop-penology and ecophysiology (Rafique et al., 2023). This is particularly evident in southern Tunisia, where low rainfall and high temperatures restrict agricultural productivity (Nasri et al., 2020). These climatic constraints, combined with the region's fragile ecological balance and limited water resources, emphasize the urgent need for sustainable agricultural approaches to mitigate climate change impacts and enhance food security (Rebouh et al., 2019). Agricultural systems in semi-arid and arid regions often rely heavily on chemical fertilizers, which contribute to soil nutrient leaching, a decline in soil microorganisms, and increased greenhouse gas emissions (Lal et al., 2021; Smith et al., 2021). To address these issues, innovative farming practices that promote soil health while minimizing environmental pollution must be implemented (Rebouh et al., 2023). Intercropping, especially cereal-legume combinations, has been emphasized as a promising strategy to enhance nutrient cycling and improve agricultural sustainability in arid and semi-arid regions (Attallah et al., 2024; Hamdi et al., 2024; Souid et al., 2024). Chickpea, a key legume species, supports soil fertility by facilitating biological nitrogen fixation through symbiotic relationships with soil bacteria (Jensen et al., 2020; Nasri et al., 2020; Sajjad et al., 2021). The integration of legumes and cereals in intercropping systems has been shown to improve soil structure, increase water use efficiency, and promote biodiversity, thereby enhancing the resilience of agriculture to climate change and extreme weather events (Litke et al., 2018; Raseduzzaman & Jensen, 2020; Cong et al., 2021). To optimize these cropping systems, modeling approaches provide valuable tools to simulate the interactions among crops, soil, water, climate, and management practices (Rafique et al., 2024; Banerjee et al., 2025). Crop modeling enables the assessment of resource use, productivity, and environmental sustainability under different scenarios (Latati et al., 2019, Agbangba et al., 2024). The STICS model (Multidisciplinary Simulator for Standard Crops) is recognized by its ability to integrate plant growth and nutrient dynamics, making it suitable for Mediterranean-type agroecosystems (Brisson et al., 1998; Rafique et al., 2024). This model incorporates climate, soil properties, and agronomic data to simulate important processes such as nutrient cycling and water balance, offering valuable insights for improving agricultural practices in water-scarce regions. Furthermore, integrating intercropping dynamics into such models allows for a more precise assessment of sustainable intensification strategies tailored to the Mediterranean environments. Despite advancements in crop modeling, accurately simulating crop growth, soil water dynamics, and nitrogen balance at the field level remains challenging. This is due to the spatial and temporal variability of the soil conditions and microbial processes influencing the nutrient dynamics (Gambín & Duvall, 2019). Additionally, the limited availability of high-resolution daily input data complicates the model evaluation, making it difficult to determine whether discrepancies arise from input data inaccuracies or model formulation errors (Del Grosso et al., 2001). Among them, the STICS model is widely used for simulating crop production and soil processes in Mediterranean environments. Although alternative models such as APSIM, DSSAT/CROPGRO, or CropSyst may better support the simulation of cereal-legume systems, STICS was chosen in this study due to its availability, adaptability to local conditions, and the research team's expertise. This study aims to evaluate the performance of the STICS model in simulating durum wheat-chickpea intercropping system in the semi-arid Mediterranean conditions of southern Tunisia where this intercropping system plays a crucial role in improving productivity, resilience, and climate adaptation for local farmers and to identify limitations and potential improvements for its application in sustainable cropping systems. Based on field experiments conducted in the Medenine region over two growing seasons, we assessed the model's accuracy in predicting key agricultural indicators, including nitrogen uptake, grain yield, and soil nitrogen and carbon content. Furthermore, we explored potential complementarities between durum wheat and chickpea in terms of nitrogen and carbon resource utilization. By achieving these objectives, this research contributes to the development of sustainable intensification strategies that are tailored to local conditions, enhancing the resilience and productivity of semi-arid agricultural systems, while promoting efficient resource management and climate adaptation.

This is one of the first attempts to apply STICS for such intercrops in this specific agroclimatic zone, contributing to the modeling literature by integrating legume parameters calibrated with experimental data from local field trials. Furthermore, this work provides insights into the challenges of simulating nitrogen dynamics in legume-cereal systems in semi-arid climates and proposes pathways for model refinement.

MATERIALS AND METHODS

Characterization of the study site

The study was conducted at the agricultural station in Medenine, in south-eastern Tunisia (33°29'58.64" N, 10°38'31.05" E), over two cropping seasons: 2020–2021 and 2021–2022. The field experiments were conducted in southern Tunisia, characterized by a Mediterranean semi-arid climate with average annual rainfall of 250 mm and mean temperatures ranging from 12 °C in winter to 30 °C in summer. The main soil properties, including texture (sand, silt and clay content), calcium carbonate content ($CaCO_3$), pH and organic matter, were analyzed at different depths (Table 1). The soil texture was predominantly sandy loam up to 100 cm depth and offered no physical barriers to root development. In addition, the soil was alkaline and low in nitrogen (N) and phosphorus (P). To parameterize the STICS model, physical and hydraulic properties, such as the bulk density and moisture content were determined (Table 1).

Table 1. Climate, soil physicochemical, and hydraulic properties of the field experiment site

Soil depth (cm)	0–20	20–40	40–60	60–80	80–100
Clay (%)	8.7	9	11.3	12.5	16.7
Silt (%)	20.1	22.6	21.4	27.3	32
Sand (%)	70.2	68.2	67	60.2	51.3
CaCO3 (%)	21	19.4	15.6	11.3	10.8
OM ($g.kg^{-1}$)	1.21	1.13	0.87	0.65	0.49
Total N ($mg\ kg^{-1}$)	3.58	5.47	6.2	7.86	6.33
Total P ($mg\ kg^{-1}$)	5.95	7.23	8.43	6.25	6.71
Available P ($mg\ kg^{-1}$)	0.51	0.86	1.17	0.74	0.93
pH	8.02	7.89	7.8	7.63	7.56
Bulk density ($g\ cm^{-3}$)	1.3	1.19	1.27	0.91	1.16
HMNIF ($m^3\ m^{-3}$)	0.11	0.12	0.12	0.13	0.14
HCCF ($m^3\ m^{-3}$)	0.23	0.23	0.25	0.27	0.27

Experimental design

The study focused on two plant varieties: chickpea (*Cicer arietinum L. 'Amdoun'*) and durum wheat (*Triticum turgidum ssp. durum L. 'Simeto'*), grown either in monoculture or in an intercropping system. The experimental design consisted of a split-plot layout with three replicates (blocks). Each sub-plot was assigned one of the following treatments: Chickpea monoculture (ChKp-MC), durum wheat monoculture (DuWh-MC), or intercropping of both crops (DuWh-IR and ChKp-IR) (3 subplots (4.5 m²) × 3 treatments × 3 replicates) (Fig. 1). The total area of the trial plot was 40.5 m², with each subplot measuring 4.5 m² and spaced 1 m apart (Fig. 1).

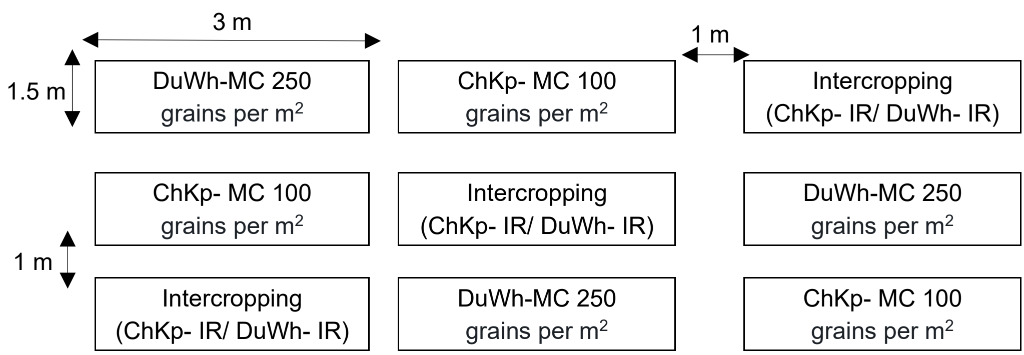

Figure 1. Experimental design including durum wheat–monocrops (DuWh-MC), chickpea-monocrops (ChKp–MC), and intercrops of durum wheat and chickpea (DuWh-IR and ChKp-IR).

At sowing, the grain densities for each treatment were as follows: 100 ± 5 grains per m² for chickpea monoculture (ChKp-MC), 250 ± 3 grains per m² for durum wheat monoculture (DuWh-MC), 50 ± 3 grains per m² for chickpea intercrops (ChKp-IR) and 150 ± 5 grains per m² for durum wheat intercrops (DuWh-IR). Sowing occurred in the third week of January of the respective growing season, with occasional manual weeding. No chemical fertilizers or herbicides were used during the entire trial. Before sowing, a soil sample was taken from each subplot at a depth of 20 cm and mixed to form a composite sample, which was referred to as bulk soil (S-bulk).

Assessments

The development phases of the two crops were recorded, focusing on the time of emergence (BBCH = 09) and flowering (BBCH = 65). Initial soil samples were taken at each sowing date to assess the soil properties and the initial water and mineral nitrogen content of the soil. Plant and soil samples were taken at five different times during the two growing seasons: two during the vegetative phase, two during chickpea flowering (110 DAS) and a final sample at harvest. At each sampling, parameters such as soil water and nitrogen content were measured at depths of 0–20 cm, 20–40 cm, 40–60 cm and 60–80 cm, as well as above-ground dry biomass and plant nitrogen uptake. In addition, soil moisture was monitored at 10-cm intervals throughout the study. Established methods were used for the physico-chemical soil analyses. The Kjeldahl method (Lynch & Barbano, 1999) was used to determine the nitrogen content in the soil, while the phosphorus content was measured using the Malachite Green method after digestion with perchloric and nitric acid (Rahutomo et al., 2019). The organic matter content of the soil was determined using the Anne method (McBratney et al., 2000) and the calcium carbonate content was determined using the Horton and Nelson method (Leo, 1963). The pH value of the soil was determined using a pH meter (Shen et al., 1996) in a suspension of soil and deionized water in a ratio of 1:2.5. The nitrogen uptake of the plants, measured in t ha^{-1}, was calculated by multiplying the dry biomass by the nitrogen concentration in the plant tissue. To obtain this value, the original nitrogen content of the seeds was subtracted from the total nitrogen in the biomass and from the nitrogen content in the grains.

Presentation of the STICS model

STICS is a plant model that works with a daily time step and is driven by thermal time, as described by Brisson et al. (2003). The model focuses on plant development by simulating shoot biomass and leaf area index (Brisson et al., 2008) and dynamically models biomass production, canopy development and root growth, including nitrogen and water uptake (Falconnier et al., 2019). The yield formation processes in STICS include grain production and filling and allow the simulation of dry matter and nitrogen accumulation in the grains, taking into account factors such as N availability, water and heat stress and anoxia. For intercropping systems, STICS uses a simplified approach by dividing the canopy into a main layer and a sub-layer, which in turn are divided into shaded and sunlit areas. This structure allows the estimation of the microclimate using a radiation balance (Brisson et al., 2004). The model offers two methods for radiation absorption: Beer's law for homogeneous crops and a radiation transfer method for row crops. For plant water requirements, STICS uses the potential evapotranspiration coefficient method or, if Beer's law is not directly applicable, the resistance method based on the Shuttleworth and Wallace model (Brisson et al., 1998). The model requires input data on soil, climate, cultivation methods, and crop-specific parameters. The soil parameters were determined based on analyses and calculations and combined with climate data on temperature, radiation, precipitation, wind speed and humidity. The inputs for crop planning include planting density, sowing date and depth as well as the irrigation schedule, whereby a soil depth of 80 cm is assumed for the calculation of the nitrogen and water reserves. Sowing dates were simulated based on seed moisture content and seedling density to allow realistic simulations. For each cropping system and season (2020–2021 and 2021–2022), specific cropping files were developed for pure durum wheat, pure chickpea and mixed crops of wheat and chickpea, resulting in eight simulation units (USMs). These USMs combine the climate, soil, and management of four cropping systems over two years. This detailed setup enables the precise calibration and simulation of different scenarios and provides robust results.

Model Calibration

The calibration of STICS for chickpea, durum wheat and their intercropping was carried out in three steps. For chickpea, a literature search was conducted in the first step, using the initial values of the pea model and adjusting the leaf area index (LAI) according to the recommendations of Brisson et al. (2008). In addition, the plant coefficient for the water requirement was set to a maximum (kmax = 1) according to Garofalo et al. (2009). In the second step, four key parameters were defined directly based on the experimental data: the minimum and maximum number of grains per unit area, the maximum grain weight, and the maximum plant height. In the final step, an optimization was carried out according to Guillaume et al. (2011), in which aspects such as phenological development, root and shoot growth, biomass distribution, nitrogen uptake, nitrogen fixation potential and yield formation were taken into account. The Javastik tool was used for this optimization, which tracks the growth stages, plant and soil additives, and yield values. For durum wheat, the calibration was carried out using the proven method, focusing on the *Simeto* variety, with initial results also obtained for the *Acalou* variety. This method corresponded to the method used for chickpea and did not require any additional information. Beer's law was used to simulate radiation absorption, the plant coefficient was used to calculate the water requirement, and the Penman model was used to estimate the potential evapotranspiration.

Parameter calibration was performed for chickpea using experimental data from the field trials. Key crop parameters such as phenological duration, radiation use efficiency, and nitrogen fixation capacity were adjusted iteratively to improve simulation accuracy. The calibrated parameter values are provided in Table 2.

Table 2. Key calibrated parameters for chickpea and default parameters for durum wheat used in the STICS model simulations

Parameter	Unit	Chickpea (Calibrated)	Durum wheat (Default)
Thermal time to flowering	°C·day	900	750
Thermal time from flowering to maturity	°C·day	600	550
Radiation Use Efficiency (RUE)	g MJ^{-1}	1.45	1.20
Maximum biological nitrogen fixation rate	kg N ha^{-1} per stage	25	N/A
Specific Leaf Area (SLA)	m^2 kg^{-1}	25	22
Maximum rooting depth	cm	100	120

Statistical Analysis and Model Evaluation

The performance of the STICS model was evaluated both graphically and quantitatively using several statistical indicators: Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMSE), model Efficiency (EF), and the Pearson correlation coefficient (R^2). RMSE (Eq. 1) quantifies the model's prediction error, with lower values indicating greater accuracy:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}} \qquad (1)$$

NRMSE (Eq. 2) normalizes the RMSE, making it easier to compare across different scales:

$$\mathrm{NRMSE} = \left(\frac{\mathrm{RMSE}}{\bar{O}}\right) \times 100 \qquad (2)$$

EF (Eq. 3) evaluates the model's predictive power by comparing the variance of the prediction errors with the variance of the observed data:

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad (3)$$

R^2 (Eq. 4) assesses the correlation between observed and simulated values, indicating how well the model captures the observed data variability:

$$R^2 = \left(\frac{\sum_{i=1}^{n} (S_i - \bar{S})(O_i - \bar{O})}{\sigma_S \sigma_O}\right)^2 \qquad (4)$$

Here, O_i and S_i represent the observed and simulated values for the i^{th} measurement, $\bar{O}$ and S are the means of the observed and simulated values, n is the total number of observations, and σS and σO are the standard deviations of the simulated and observed values, respectively. Using these indicators provides a thorough evaluation of the model's performance.

RESULTS

Yield Predictions

The STICS model showed different efficiencies in predicting durum wheat and chickpea yields for the cross and monocultures in the two cropping seasons (2020–2021 and 2021–2022) (Fig. 2). In the 2020–2021 season, the model showed a good prediction for durum wheat with efficiency coefficients (EFF) of 0.62 and 0.55 and normalized root mean square errors (NRMSEs) of 30.78% and 37.56% for the monoculture and intercropping systems, respectively. Accordingly, the R^2 values of 0.90 and 0.81 show a good correlation with the observed and simulated values. In contrast, the predictions for chickpea in monoculture and intercropping showed greater inconsistency with EFF values of 0.19 and 0.12 and NRMSE values of 54.05% and 51.67%, associated with low R^2 values of 0.44 and 0.37, respectively. In the 2021–2022 season, the performance of the model was still good in the case of durum wheat, with corresponding EFF values of 0.63 and 0.57 and NRMSE values of 29.3% and 32.14% for the monoculture and intercropping systems, respectively. The R^2 values of 0.89 and 0.84 contributed to the reliability of the model for predicting wheat yields. For chickpea, predictions declined further, with EFF values of 0.15 and 0.03 and NRMSE 60.6% and 78.6% for monocultures and intercropping systems, respectively, associated with low R^2 values of

0.31 and 0.27, respectively. These differences emphasize the difficulties in simulating chickpea yields, especially in intercropping systems, which are probably due to uncalibrated parameters related to nitrogen fixation processes and pest interactions. As shown in Fig. 2, the STICS model was generally more successful in predicting durum wheat yields than chickpea yields, which requires intensive improvement of parameter calibration for better prediction of legumes in agricultural multi-crop systems.

Nitrogen Absorption (AGPN)

During two seasons (2020–2021 and 2021–2022), the STICS model simulated the nitrogen uptake by plants (AGPN) in the monoculture and intercropping systems for durum wheat and chickpeas. Monocultures performed better with EFF values of 0.63 for chickpea and 0.69 for wheat, while the intercropping systems had lower values of 0.47 and 0.56, respectively. NRMSE values were also lower for both crops in monocultures, with 39 for chickpea and 24 for wheat compared to 42 and 29 in intercropping. The significantly high NRMSE value for chickpea emphasizes the complex nitrogen dynamics in intercropping, which is influenced by the interactions of the rhizobia symbiosis. In the second season, chickpea intercropping performed better than monocropping (EFF: 0.58, NRMSE: 16.85), while the performance of wheat decreased, especially in monocropping (EFF: 0.25, NRMSE: 44.73). The regressed data in Fig. 3 show a significant equalization of the simulated and observed AGPN for wheat, especially in monocultures. This indicates that the model should be further improved, especially to support wheat monocultures and chickpea intercrops, considering biological nitrogen fixation among other complex variables.

Nitrogen Stock in Soil

The STICS model was run to simulate soil nitrogen stocks under monocropping and intercropping practices for durum-wheat and chickpea over two cropping seasons from 2020 to 2021 and from 2021 to 2022, respectively. For the chickpea monoculture, an EFF of 0.54 with an NRMSE of 27.43 was obtained for the 2020–2021 season, indicating a good predictive ability of the model in terms of its parameters (Fig. 4). For the 2021–2022 seasons, however, the model underperformed, showing an EFF of 0.18 and an NRMSE of 58.7. Therefore, similar trends developed in the chickpea intercropping systems with EFF values of 0.62 and an NRMSE of 32.5 for 2020–2021 compared to an EFF value of 0.29 and an NRMSE of 54.92 in the 2021–2022 season. For wheat monocultures, the model showed moderate performance with EFF values of 0.38 and 0.76 in the 2020–2021 and 2021–2022 seasons, respectively, resulting in NRMSE values of 44.12% and 64.2%. For the wheat intercropping systems, an EFF of 0.41 was observed in the 2020–2021 season, while the EFF in the 2021–2022 season was 0.25 and the NRMSE was 31.3% and 55.7%, respectively. Moreover, the regressive analysis also suggested that the STICS model performed better in estimating soil nitrogen stocks in 2020–2021 than in 2021–2022 for both cropping systems. The observed deviations in the years 2021 to 2022 could be due to fluctuations in the environment and nitrogen losses due to leaching or other factors that were not considered when adjusting the model parameters.

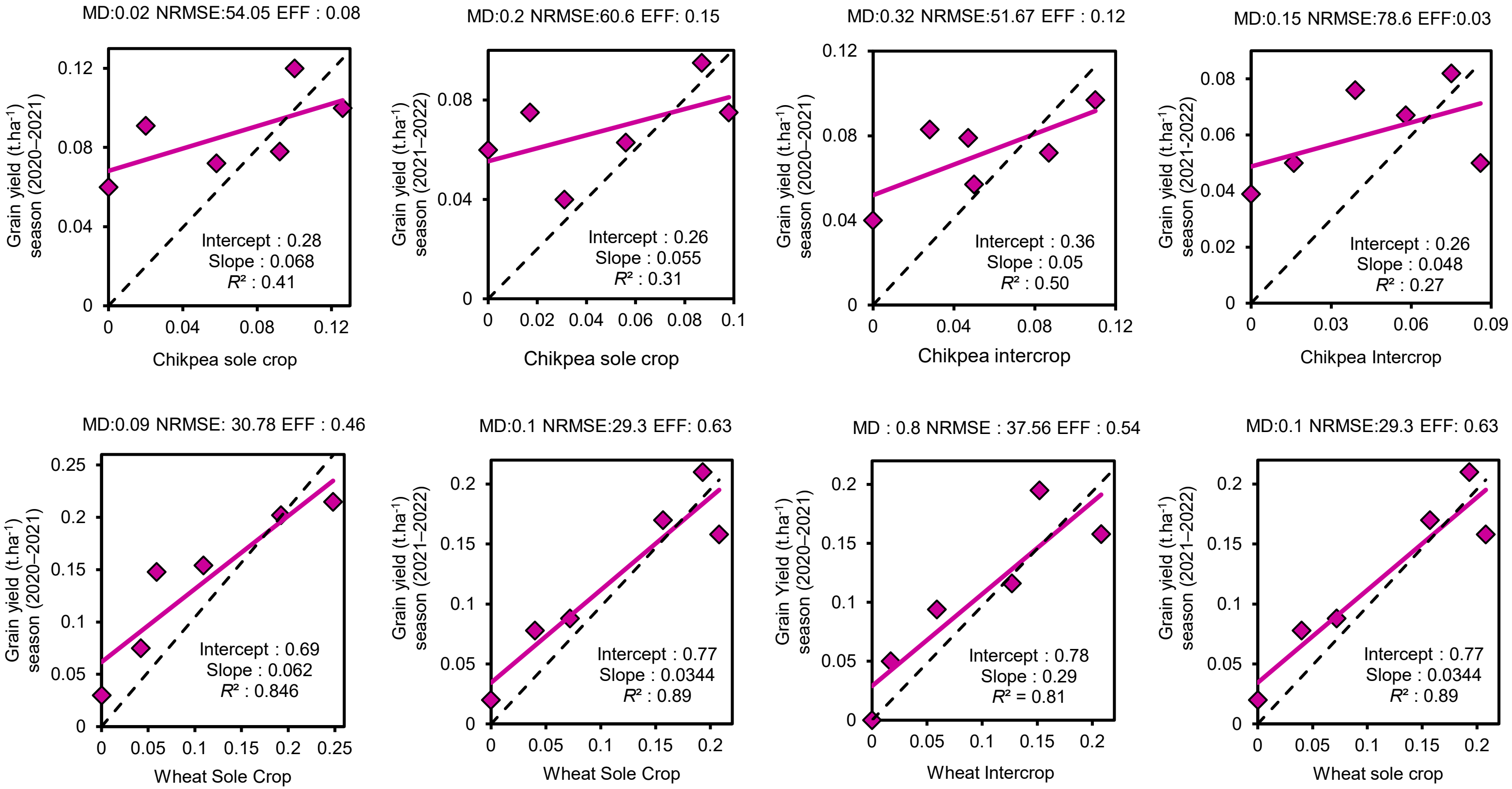

Figure 2. Comparison of observed (X-axis) and STICS-simulated (Y-axis) grain yield for calibrated data of durum wheat and chickpea grown in monoculture and intercropping systems over two seasons (2020–2021) and (2021–2022). NRMSE = Normalized Root Mean Square Error, EFF = Model Efficiency, MD = Mean Deviation. The pink line represents the regression of simulated values against observed values, and the dashed line represents the 1:1 line.

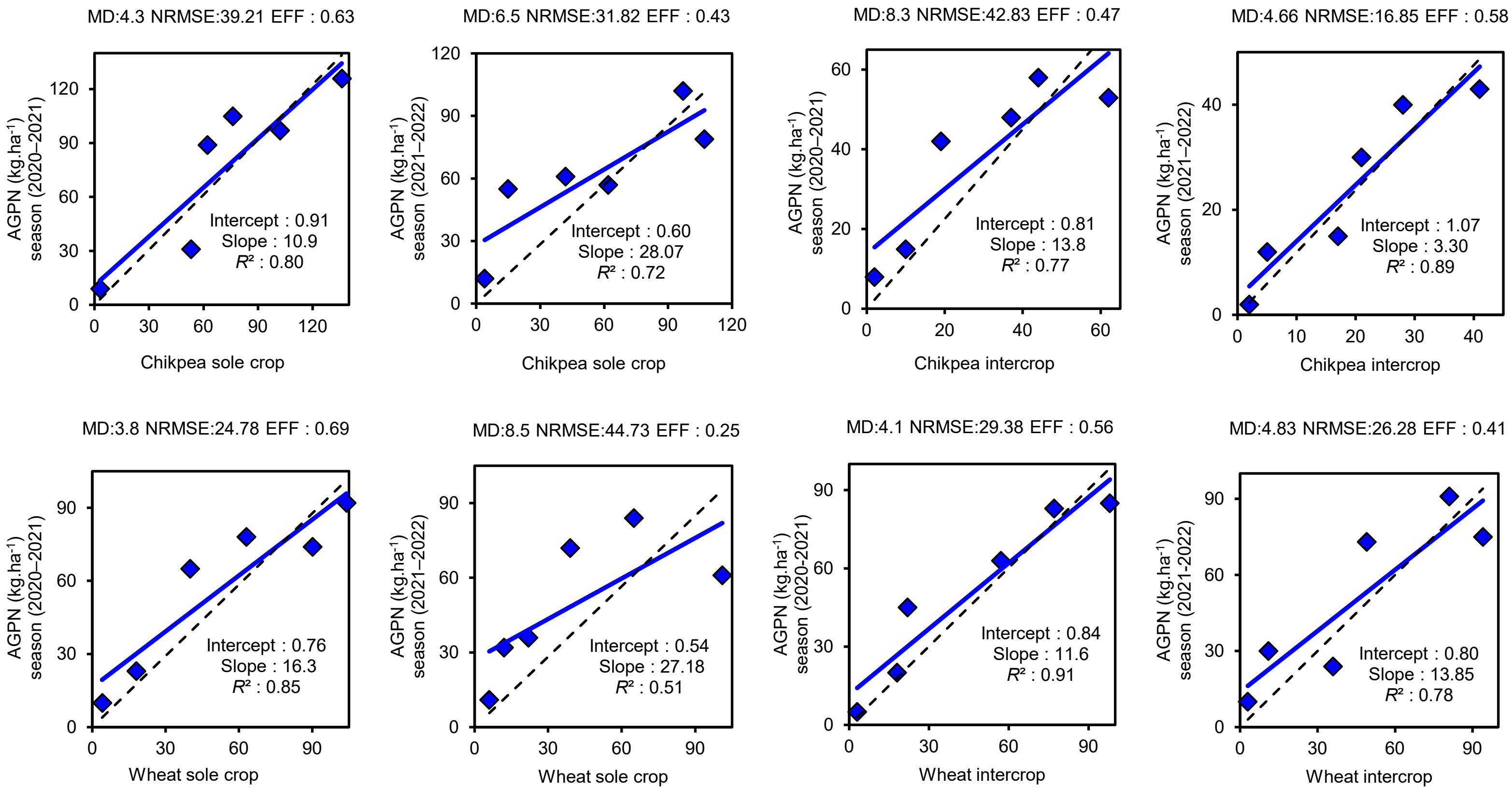

Figure 3. Comparison of Observed (X-axis) and STICS-Simulated (Y-axis) Plant Nitrogen Uptake (AGPN) for Two Years of Calibrated Data (2020–2021 and 2021–2022). NRMSE = Normalized Root Mean Square Error, EFF = Model Efficiency, MD = Mean Deviation. The solid blue line represents the regression of simulated values against observed values, and the dashed line represents the 1:1 line.

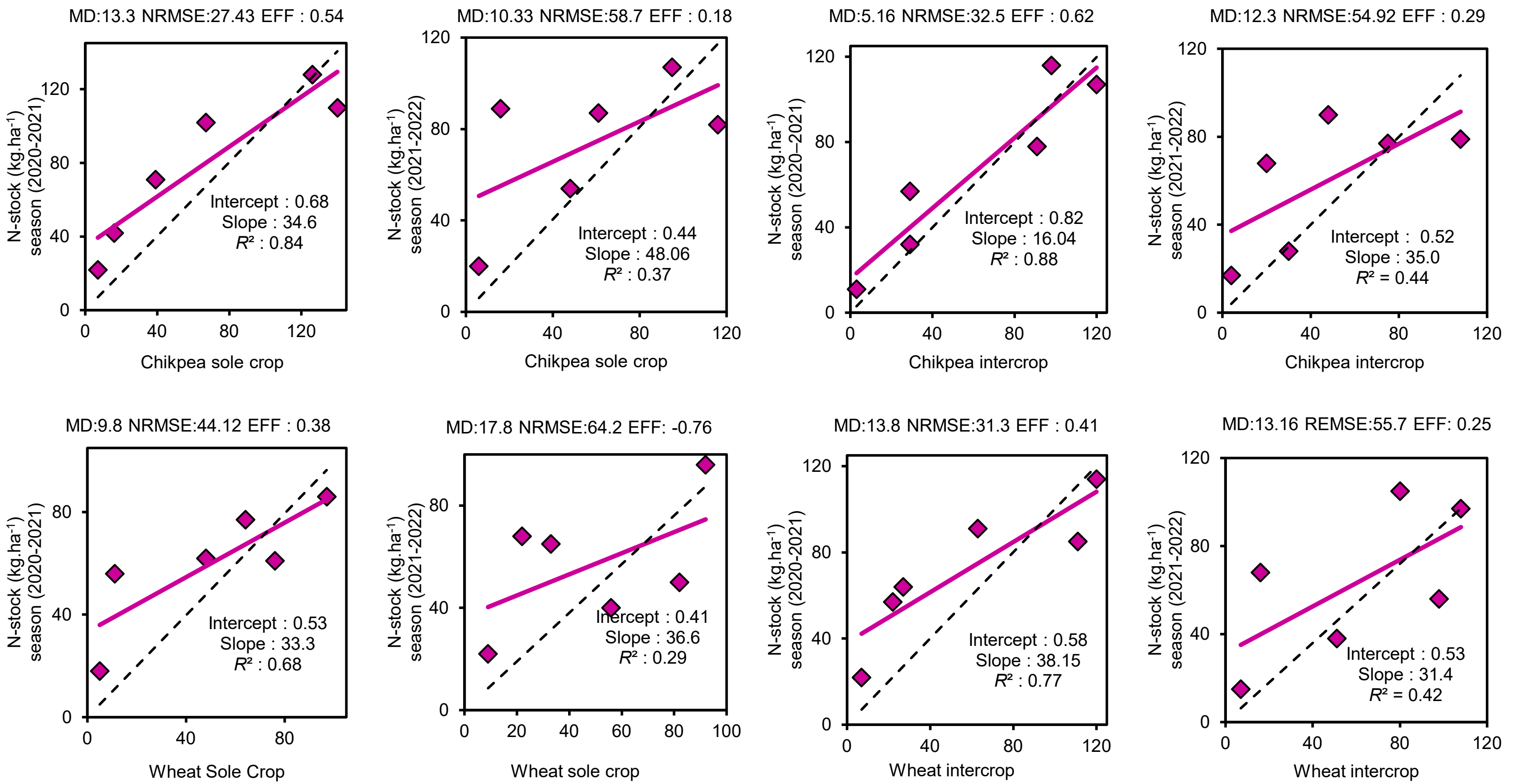

Figure 4. Comparison of Observed (X-axis) and STICS-Simulated (Y-axis) Soil Nitrogen Stocks for Two Years of Calibrated Data (2020–2021: A and 2021–2022: B). NRMSE = Normalized Root Mean Square Error, EFF = Model Efficiency, MD = Mean Deviation. The solid pink line represents the regression of simulated values against observed values, and the dashed line represents the 1:1 line.

Carbon Stocks

For both cropping systems, the soil carbon stocks for durum wheat in the second cropping season (2021–2022) were calculated following initial calibration of the soil properties using the STICS model (Fig. 5). The efficiency coefficients (EFF) confirmed a reasonable agreement between the experimental and simulated values of the soil carbon stocks, which were evaluated in the range of 0.47–0.57 (Fig. 5). This is complemented by the normalized root mean square errors (NRMSEs) of 17.34–27.2, highlighting the ability of the STICS model to explain soil carbon dynamics under different cropping systems. This season, the chickpea model performed quite well with EFF values of 0.50 and 0.57 for intercropping and monocropping, respectively. This means that the model was able to adequately capture the specific properties of legumes, such as their contribution to carbon fixation, as evidenced by the high agreement of the simulated soil carbon stocks with the field measurements. However, for the first cropping season (2020–2021), the prediction quality deteriorated for both species in the intercropping systems with EFF values of 0.44 for chickpea and 0.49 for durum wheat. In the monocultures, the EFF values were 0.63 for chickpea and 0.50 for durum wheat. These results indicate that the STICS model encounters obstacles in successfully simulating carbon dynamics under these specific conditions, mainly due to the complex crop-soil interactions and the variation in environmental aspects that are not fully accounted for.

Soil Water Stocks

The STICS model provided satisfactory simulation performance for the soil water content during the first growing season (2020–2021) for chickpea and durum wheat grown as monocultures as well as for mixed crops. The efficiency of the model, expressed as efficiency factors (EFF), was as follows: Chickpea monoculture-0.53, Chickpea intercropping-0.51, wheat monoculture-0.61, and wheat intercropping-0.58 (Fig. 6). The NRMSE values were also low, ranging from 24.75 to 37.2, confirming the model's good ability to capture the soil water dynamics during this period. However, in the second growing season (2021–2022), the model struggled to simulate the soil water content under monoculture conditions. The efficiency values decreased significantly: EFF of 0.18 for chickpea monocultures, 0.23 for chickpea intercrops, 0.16 for wheat monocultures and 0.33 for wheat intercrops. The NRMSE was very high: chickpea intercrop-52.2, wheat monocrop-71.31, chickpea monocrop-66.2, while wheat intercrop gave a slightly better model performance with an NRMSE of 57.8. Thus, variations in soil moisture during this season were caused by interactions such as root competition, soil heterogeneity, and environmental factors influencing water availability. Thus, while the STICS model shows potential for predicting soil water supply under certain conditions, in this case 2020–2021, great efforts still need to be made to improve its reliability in different cropping systems and different environments.

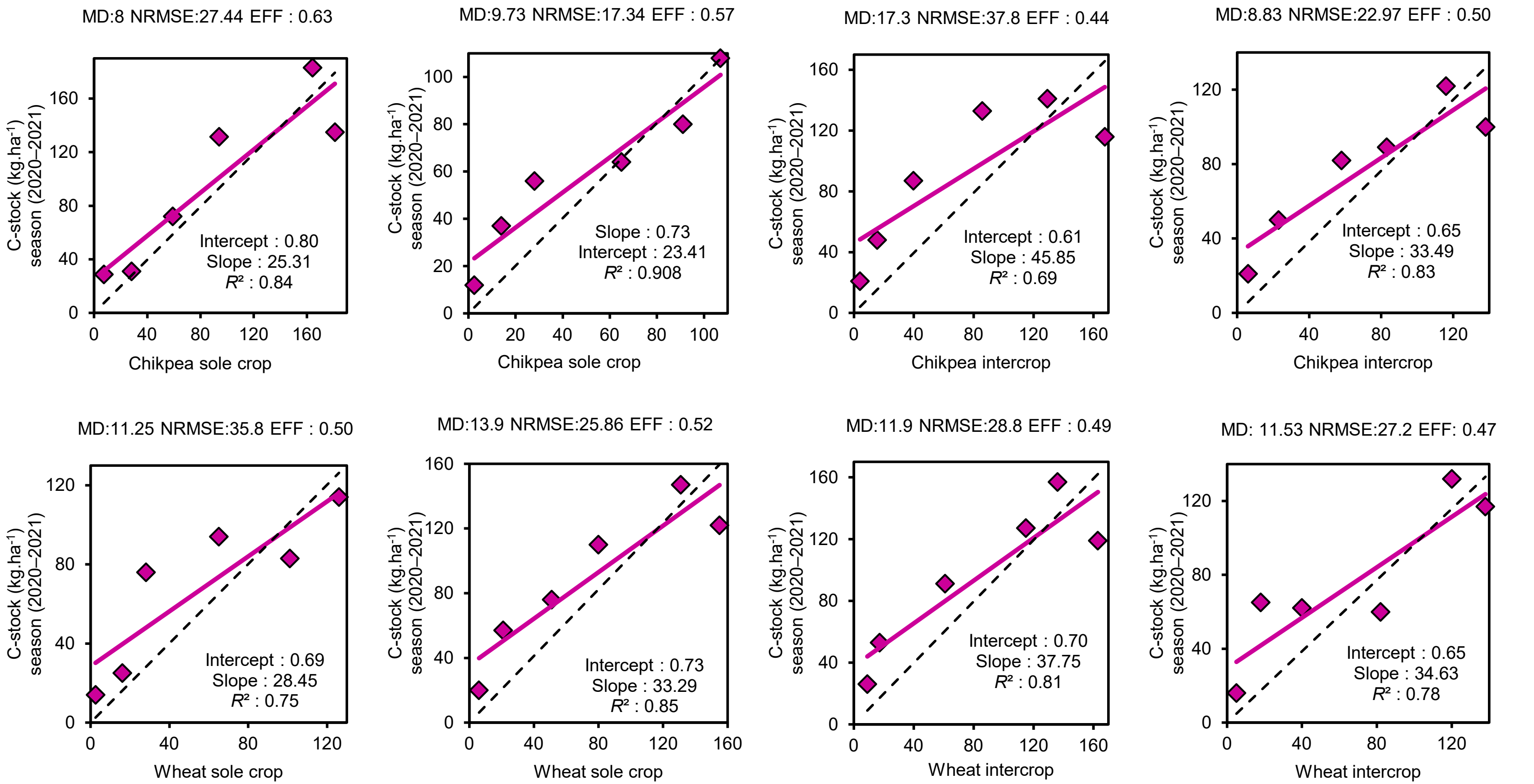

Figure 5. Comparison of Observed (X-axis) and STICS-Simulated (Y-axis) Soil Carbon Stocks for Two Years of Calibrated Data (2020–2021 and 2021–2022). NRMSE = Normalized Root Mean Square Error, EFF = Model Efficiency, MD = Mean Deviation. The solid pink line represents the regression of simulated values against observed values, and the dashed line represents the 1:1 line.

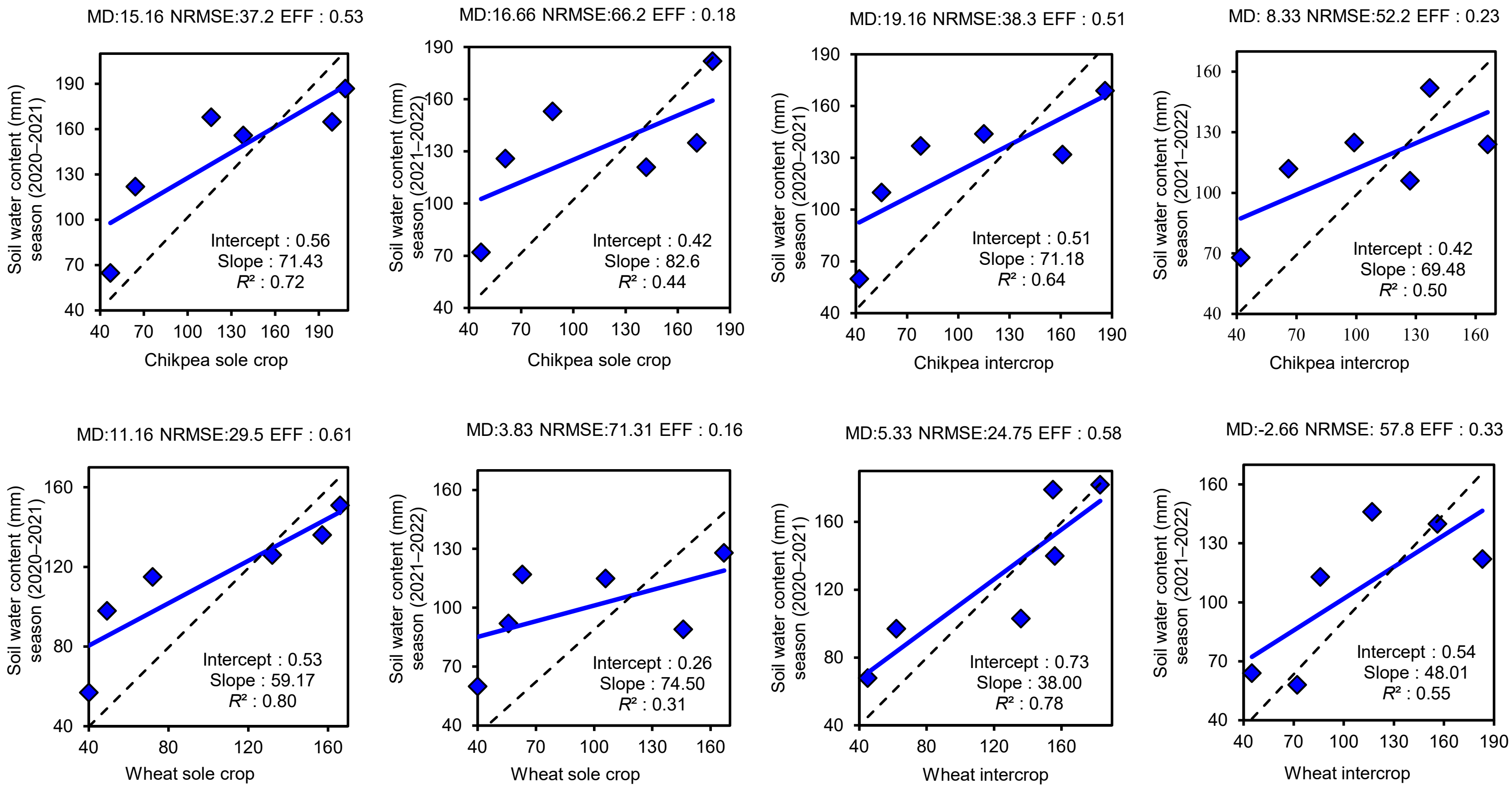

Figure 6. Comparison of observed (X-axis) and STICS-Simulated (Y-axis) Soil Water Content for Two Years of Calibrated Data (2020–2021 and 2021–2022). NRMSE = Normalized Root Mean Square Error, EFF = Model Efficiency, MD = Mean Deviation. The solid blue line represents the regression of simulated values against observed values, and the dashed line represents the 1:1 line.

DISCUSSION

Model calibration and valuation accuracy

We have observed a general trend in our analysis: The STICS model tends to overestimate low yield values and underestimate high yield values and other parameters. This observation suggests possible underlying issues, such as uncalibrated parameters or the unique characteristics of the agricultural systems analyzed, which may cause the model to misestimate yields. As the STICS model was originally developed for systems in temperate climates and monocultures, it may have difficulty fully capturing the complexity of intercropping systems and the subtropical climate conditions in our study. This emphasizes the challenge of applying this model to different agricultural environments where environmental conditions and crop interactions result in variability that the model cannot fully capture. Parameter calibration remains a critical issue. Some parameters, especially those related to nitrogen fixation in legumes and crop-soil interactions, may not have been adequately calibrated. Previous studies (e.g., Paleari et al., 2017; Doltra & García-Vera, 2020; Zhang & Zheng, 2021; L'taief et al., 2024) have reported similar problems when applying crop models to different climates and cropping systems. These results suggest that while STICS is effective in certain environments, its application in different cropping systems warrants further calibration and refinement.

Evaluation of the predictions of the STICS model

Our observations show that the STICS model effectively predicts durum wheat yields in the two cropping seasons (2020–2021 and 2021–2022). The researchers showed that the model effectively simulates wheat production in different cropping systems. The corresponding efficiency coefficients (EFF) of 0.62 in monoculture and 0.63 in intercropping illustrate the predictive power of the model. Similar models as APSIM (Agricultural Production Systems Simulator), DSSAT (Decision Support System for Agrotechnology Transfer) and WOFOST (World Food Studies) were effective in predicting wheat yields under different conditions, as other studies have shown (e.g. (Hatfield & Prueger, 2019; Rafique & Leclère, 2021)). In contrast, the predictions of the STICS model for chickpea yields were less accurate, with average efficiency coefficients of 0.27 observed in both cropping seasons. High normalized root mean square errors (NRMSE) of 51 and 78% highlight the difficulties associated with modeling chickpea yields. These discrepancies may also be due to the fact that the dynamics of nitrogen fixation are less well understood by the model, as well as pest interactions and specific plant responses to environmental stress, as addressed in corresponding studies by Louarn et al. (2018). In addition, the complexity of the simulation functions for nitrogen uptake limits the usefulness of the model. The model performed relatively well in the wheat monocultures in terms of nitrogen dynamics, with NRMSE values of 24% and 44%, but had problems in the intercropping systems where the NRMSE exceeded 50%. The worst scenario was observed in chickpea, as the NRMSE values often exceeded 60% when simulating nitrogen uptake. The challenges were consistent with the results of Gambín & Duvall (2019), who showed that the models underestimated the contribution of legumes to biological nitrogen fixation. This simulation of soil nitrogen stocks was more reliable during the 2020–2021 season compared to 2021–2022. This variation may be due to environmental factors such as rainfall patterns and temperature fluctuations, which influence nitrogen mineralization and leaching processes. The model's current configuration may not fully account for these temporal environmental variations, suggesting a need for incorporating more dynamic environmental parameters. Regarding soil carbon stocks, the model performed well in the first season, especially for the wheat systems ($R^2 = 0.85$). However, the performance in the second season indicate different results as first season, with R^2 values of 0.70 for the chickpea monocultures. These discrepancies are likely due to the limitations of the model in accounting for highly complex plant-soil interactions under changing environmental conditions, as noted by Kherif et al. (2022). The model predictions of the soil water content showed satisfactory results in the first season with EFF = 0.53–0.61, while the performance decreased drastically in the second season (EFF = 0.16–0.33). The higher NRMSE values observed in 2021–2022 indicate that the model had difficulty accounting for soil heterogeneity, root competition and other factors affecting water availability, which is in line with the findings of Ripoche & Leclère (2021). In terms of nitrogen uptake (AGPN), the model showed better accuracy in monoculture systems than in intercropping setups. This could be attributed to the simplified nitrogen dynamics in monocultures, whereas intercropping introduces additional variables like interspecies competition and facilitation, which complicate nitrogen uptake patterns. These findings align with previous studies that highlight the challenges of modeling nitrogen dynamics in intercropping systems (e.g., Hamdi et al., 2018).

The STICS model demonstrated varying performance across different crops, cropping systems, and seasons. Notably, it consistently provided more accurate simulations for durum wheat compared to chickpea. This disparity is likely due to the model's more comprehensive calibration for cereals, whereas legumes like chickpea involve complex biological processes such as nitrogen fixation and specific pest interactions that are not fully captured by the current model parameters.

Implications for Future Research and Model Applications

The differences between the observed chickpea yields and the model's representation of nitrogen dynamics and soil carbon stocks highlight the need for more intensive studies to refine the STICS model. Future research should focus on the parameterization of specific components or the elaboration of new parameters that accurately represent the dynamics of legume and intercropping systems. This could include a more comprehensive investigation of rhizobia interactions, nitrogen fixation processes and the effects of soil management on crop performance. Future applications of the model beyond parameter optimization could investigate the wider impacts of climate change on crop production, soil carbon sequestration and water availability. The integration of long-term climate scenarios and advanced soil management options could improve the predictive power of performance in developed areas. Studies by Rosenzweig & Iglesias (2014) and Donatelli et al. (2017) show the potential benefits of such approaches to improve the accuracy and reliability of models.

Overall, while the STICS model shows promise in simulating various aspects of crop and soil dynamics, its performance is influenced by crop type, cropping system, and environmental conditions. Future improvements should focus on enhancing the model's representation of legume-specific processes, interspecies interactions in intercropping systems, and dynamic environmental factors.

Applications: Assessing climate variability and stress scenarios

To expand the scope of this study, we conducted additional simulations to understand some of the effects of climate variability on intersystem and monoculture systems. Key scenarios included a 2 °C and 4 °C increase in temperature, a -20% decrease in precipitation, and a combined consideration of heat and drought stress. At different levels of warming, wheat yields were found to be more resilient to temperature increases than chickpea yields, with chickpea yields decreasing by up to 15% in the 4 °C scenario. In addition, in the above experiments, there was a reduction in soil nitrogen stocks due to accelerated decomposition of soil organic matter. The decrease in precipitation had significant effects on both systems, but chickpeas were more affected as their yields decreased by 25% compared to durum wheat, suggesting that legumes are more susceptible to drought stress. Combined simulations of heat and drought stress resulted in synergistic effects, with chickpea yields decreasing by up to 30% and wheat yields by 20%. Soil moisture content was also significantly reduced, especially under monoculture conditions, highlighting the potential of intercropping for more efficient water use. These results underline the role of intercropping systems in mitigating climate stress for crops, improving resource utilization and stabilizing crop yields under difficult environmental conditions. Future research should build on these results to develop adaptive strategies to optimize intercropping to increase the resilience of agriculture to climate change, as proposed by Zhang & Zheng (2021) and Ripoche & Leclère (2021).

CONCLUSIONS

This study evaluated the performance of the STICS model in simulating crop yields, nitrogen uptake, and soil carbon and water stocks in durum wheat and chickpea monocultures and intercropping systems over two growing seasons. The STICS model was able to accurately predict durum wheat yield and nitrogen uptake, while chickpea performance showed larger discrepancies. These findings highlight the need for further calibration of the model to account for the complex biological and environmental interactions present in legume crops and intercropping systems. To enhance the model's applicability, future research should focus on integrating detailed representations of nitrogen fixation processes, interspecies interactions, and dynamic environmental variables such as soil moisture and temperature fluctuations. Such improvements would increase the model's accuracy and reliability, making it a more effective tool for designing and managing sustainable cropping systems.

FUNDING: This paper has been supported by the RUDN University Strategic Academic Leadership Program.

ACKNOWLEDGMENTS: ‘The authors extend their appreciation to the Deanship of Research and Graduate Studies at King Khalid University, KSA, for funding this work through small research project under grant number RGP1/145/46’.

REFERENCES

Agbangba, E.C., Yalinkpon, F., Sossa, E.E.L., Ehnon Gongnet., Glèlè Kakaï, R. 2024. A simulation study on the comparison of Diagnosis and Recommendation Integrated System (DRIS), Modified-DRIS(M-DRIS), and Compositional Nutrient Diagnosis (CND) forpineapple nutrient diagnosis. *Agronomy Research* **22**(S3), 1380–1404. https://doi.org/10.15159/AR.24.101

Attallah, A., Hamdi, W., Souid, A., Farissi M., L'taief, B., Messiga, A.J. & Zagrarni, M.F. 2024. Impact of cereal–legume intercropping on changes in soil nutrients contents under semi–arid conditions. *Sustainability* **16**(7), 2725. https://doi.org/10.3390/su16072725

Banerjee, K., Dutta, S., Das S, & Sadhukhan, R., 2025. Crop simulation models as decision tools to enhance agricultural system productivity and sustainability – a critical review. *Technology in Agronomy* 5: e002 doi: 10.48130/tia-0024-0032

Brisson, N., Bussière, F., Ozier-Lafontaine, H., Tournebize, R. & Sinoquet, H. 2004. Adaptation of the crop model STICS to intercropping. Theoretical basis and parameterisation. *Agronomie* **24**, 409–421. https://doi.org/10.1051/agro:2004031

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Hénault, C., Maraux, F., Seguin, B. & Sinoquet, H. 2003. An overview of the crop model STICS. *European Journal of Agronomy* **18**, 309–332. https://doi.org/10.1016/S1161-0301(02)00110-7

Brisson, N., Launay, M., Mary, B. & Beaudoin, N. 2008. *Conceptual Basis, Formalisations and Parameterization of the STICS Crop Model*. Versailles: Editions Quae. Available from: https://www.quae.com/produit/1225/9782759210680/conceptual-basis-formalisations-and-parameterization-of-the-stics-crop-model

Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M.H., Ruget, F., Nicoullaud, B., Gate, P., Devienne-Barret, F., Antonioletti, R., Durr, C., Richard, G., Beaudoin, N., Recous, S., Tayot, X., Plenet, D., Cellier, P., Machet, J.M., Meynard, J.M. & Delécolle, R. 1998. STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie* **18**, 311–346. doi: 10.1051/agro:19980501

Cong, W., Lü, Y., Van Noordwijk, M. & Li, L. 2021. Intercropping legumes and cereals improves soil properties and yield stability in semi-arid regions. *Agriculture, Ecosystems & Environment* **309**, 107310. https://doi.org/10.1016/j.agee.2020.107310

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S. & Schimel, D.S., 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: Schaffer M., Ma L., Hansen S. (Eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*. CRC Press, Boca Raton, FL, USA, pp. 303–332.

Donatelli, M., Magarey, R.D., Bregaglio, S., Willocquet, L., Whish, J.P.M. & Savary, S., 2017. Modelling the impacts of pests and diseases on agricultural systems. *Agricultural Systems* **155**, 213–224. https://doi.org/10.1016/j.agsy.2017.01.019

FAO. 2020. *The State of Food Security and Nutrition in the World 2020*. http://www.fao.org/publications/sofi/2020/en/

Falconnier, G.N., Journet, E.-P., Bedoussac, L., Vermue, A., Chlébowski, F., Beaudoin, N. & Justes, E., 2019. Calibration and Evaluation of the STICS soil-crop model for faba bean to explain variability in yield and N2 fixation. *European Journal of Agronomy* **104**, 63–77.

Gambín, B.L. & Duvall, R., 2019. Challenges in modeling nitrogen dynamics in legume crops. *Field Crops Research* **230**, 96–105. https://doi.org/10.1016/j.fcr.2019.06.005

Garofalo, P., Vonella, A.V., Ruggieri, S. & Rinaldi, M., 2009. Verification of crop coefficients for chickpeas in the Mediterranean environment. *WIT Transactions on Ecology and the Environment* **125**, 493–502. https://doi.org/10.2495/WRM090441

Guillaume, S., Bergez, J.-E., Wallach, D. & Justes, E., 2011. Methodological comparison of calibration procedures for durum wheat parameters in the STICS model. *European Journal of Agronomy* **35**, 115–126. https://doi.org/10.1016/j.eja.2011.05.003

Hamdi, W., Beji, R., Ouertatani, S. & Gharbi, A. 2018. Effect of nitrogen and potassium levels on the potatoes growth in the Chott Mariem region of Tunisia. *Journal of Experimental Agriculture International* **28**(5), 1–9. https://doi.org/10.9734/JEAI/2018/20206

Hamdi, W., L'taief, B., Souid, A., Atallah, A., Telahigue, F., Moussa, M., Lazali M. & Hamidi, N. 2024. Durum wheat–chickpea intercropping improves soil phosphorus status and biomass production under small soil inputs. *Journal of Soil Science and Plant Nutrition* **24**(1), 1349–1361. https://doi.org/10.1007/s42729-024-01638-8

Hatfield, J.L., Prueger, J.H., 2019. The role of agroecosystem modeling in understanding climate change impacts on agriculture. *Agricultural Systems* **167**, 41–52. doi: 10.1016/j.agsy.2018.09.014

IPCC. 2019. Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. https://www.ipcc.ch/srccl/

Jensen, E.S., Carlsson, G. & Hauggaard-Nielsen, H. 2020. Enhancing nitrogen use efficiency of crops by introducing legume intercrops. In: *Advances in Agronomy* **160**, Academic Press. https://doi.org/10.1016/bs.agron.2019.10.006

Kherif, S., Duvall R. & Piquemal A., 2022. Calibration of the STICS model for chickpeas in Mediterranean conditions. *Field Crops Research* **274**, 108373. doi: 10.1016/j.fcr.2021.108373

Lal, R., Safriel, U., Boer, B., Wuepper, D., Nielsen, U.N., Zoebeley, E. & Singh, B.R. 2021. Soil degradation as a reason for poor crop yields: The need for sustainable soil management. *Sustainability* **13**(12), 6453. https://doi.org/10.3390/su13126453

Latati, M., Rebouh, N.Y., Aouiche, A. & Laouar, M., 2019. Modeling the functional role of the microorganisms in the daily exchanges of carbon and nitrogen in intercropping system under Mediterranean conditions. *Agronomy Research* **17**(2), 559–573.

Leo, M.W.M. 1963. Determination of soil carbonates by a rapid gasometric method. *Journal of Agricultural and Food Chemistry*, **11**(4), 452–455. https://doi.org/10.1021/jf60129a008

Litke, L., Gaile, Z. & Ruža, A. 2018. Effect of nitrogen fertilization on winter wheat yield and yield quality. *Agronomy Research* **16**, 500– 509. https://doi.org/10.15159/AR.18.064

Louarn, G., Carrère, P. & Avice, J.C. 2018. Nutrient cycling in legume-based agroecosystems: Concepts, impacts on nitrogen use efficiency and modelling. *Agronomy for Sustainable Development* **38**(6), 48. https://doi.org/10.1007/s13593-018-0538-4

L'taief, B., Alqahtani, W., Hamdi, W., Elghamdi, H., Ben Haj Ahmed, S. & Sifi, B. 2024. Inoculation of fava bean plants (Vicia faba L.) with a PGPR combination suppresses the impact of root-knot nematode and promotes plant growth. *Legume Research* **47**(9), 1592–1598. https://doi.org/10.18805/LRF-805

Lynch, J.M. & Barbano, D.M. 1999. Kjeldahl nitrogen analysis as a reference method for protein determination in dairy products. *J. AOAC Int.* **82**, 1389–1398. doi: 10.1093/jaoac/82.6.1389

McBratney, A.B., Odeh, I.O.A., Bishop, T.F.A., Dunbar, M.S. & Shatar, T.M. 2000. An overview of pedometric techniques for use in soil survey. *Geoderma* **97**, 293–327. https://doi.org/10.1016/S0016-7061(00)00043-4

Nasri, N., Baccar, R. & Nasri, M. 2020. Climate change impact on crop yield in semi-arid regions: A case study in central Tunisia. *Theoretical and Applied Climatology* **139**(3–4), 1417–1427. https://doi.org/10.1007/s00704-019-03083-4

Paleari, L., Movedi, E., Cappelli, G., Wilson, L.T. & Confalonieri, R. 2017. Surfing parameter hyperspaces under climate change scenarios to design future rice ideotypes. *Global Change Biology* **23**, 4651–4662.
Rafique, R., Ahmad, T., Ahmed, M. & Azam Khan, M. 2024. Adapting the process based STICS model to simulate phenology and yield of table grapes- a high value fruit crop in a new emerging viticulture zone of South Asia. *Scientia Horticulturae* **336**, 113419, ISSN 0304-4238. https://doi.org/10.1016/j.scienta.2024.113419
Rafique, R., Ahmad, T., Ahmed, M. & Azam Khan, M. 2023. Exploring key physiological attributes of grapevine cultivars under the influence of seasonal environmental variability. *OENO One* **57**(2), 381–397. https://doi.org/10.20870/oeno-one.2023.57.2.7091
Rafique, T., Hameed, M., Naseer, M., Rafique, R., Sadiq, R., Zikreae, A. & Sajjad, M.R. 2021. Comparative Leaf Anatomy of Grasses (Poaceae) in Faisalabad Region of Pakistan. *Polish Journal of Environmental Studies* **30**(6), 5701–5709. https://doi.org/10.15244/pjoes/136043
Rahutomo, S., Kovar, J.L. & Thompson, M.L. 2019. Malachite Green method for determining phosphorus concentration in diverse matrices. *Communications in Soil Science and Plant Analysis* **50**(14), 1743–1752. https://doi.org/10.1080/00103624.2019.1635140
Raseduzzaman, M. & Jensen, E.S. 2020. Legume-cereal intercropping: A sustainable way to intensify agriculture. *Plant and Soil* **451**(1–2), 1–22. doi: 10.1007/s11104-019-04395-y
Rebouh, N.Y., Polityko, P.M., Pakina, E., Plushikov, V.G., Norezzine, A., Gadzhikurbanov, A., Vvedenskiy, V., Duksi, F. & Iguer-Ouada, M. 2019. Impact of three integrated crop protection treatments on the varieties of winter wheat (*Triticum aestivum* L.) in Moscow area, Russia. *Research on Crops* **20**(1), 161–168. doi: 10.31830/2348-7542.2019.022
Rebouh, N.Y., Khugaev, C.V., Utkina, A.O., Isaev, K.V., Mohamed, E.S. & Kucher, D.E. 2023. Contribution of eco-friendly agricultural practices in improving and stabilizing wheat crop yield: A review. *Agronomy* **13**, 2400. https://doi.org/10.3390/agronomy13092400
Ripoche, D. & Leclère, H. 2021. Soil water dynamics modeling in agricultural systems: Advances and challenges. *Field Crops Research* **266**, 108159. doi: 10.1016/j.fcr.2021.108159
Rosenzweig, C. & Iglesias, A. 2014. Impacts of climate change on agriculture: A global perspective. *Agricultural Systems* **124**, 115–125. https://doi.org/10.1016/j.agsy.2013.12.001
Sajjad, M.R., Rizvi, S.A., Rafique, R., Naseem, W., Khan, A., Muhammad, G., Subhani, A., Aziz, M. & Javid, S. 2021. Characterization of cowpea to harvest rainwater for wheat in semiarid conditions. *Spanish Journal of Agricultural Research* **19**(3), e1201. https://doi.org/10.5424/sjar/2021193-16645
Shen, A.L., Li, X.Y., Kanamori, T. & Arao, T. 1996. Effect of long-term application of compost on some chemical properties of wheat rhizosphere and non-rhizosphere soils. *Pedosphere* **6**(4), 355–363.
Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F. & Tubiello, F.N. 2021. Agriculture, forestry and other land use (AFOLU). 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. https://www.ipcc.ch/report/ar6/wg1/
Souid, A., Hamdi, W., L'taief, B., Attallah, A., Hamdi, N., Alshaharni, M.O. & Zagrarni, M.F. 2024. The potential of durum wheat–chickpea intercropping to improve the soil available phosphorus status and biomass production in a subtropical climate. *PLOS ONE* **19**(5), e0300573.
Zhang, L. & Zheng, H. 2021. Improving the STICS model for estimating crop yields under changing climatic conditions. *Agricultural Systems* **185**, 102936. doi: 10.1016/j.agsy.2020.102936