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# Modeling growth, yield, irrigation water use and soil moisture dynamics of OPSIS-irrigated sugarcane

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The Optimized Subsurface Irrigation System (OPSIS) is a neoteric subsurface irrigation method designed for irrigating upland crops. While field trials have evaluated its performance for certain crops, further research is required to enhance its effectiveness. Utilizing crop models to assess OPSIS could reduce the need for time-consuming and costly field trials. This study aimed to enhance the modeling capabilities of the Agricultural Production Systems Simulator (APSIM) to simulate the growth, yield, water use, and soil moisture dynamics of OPSIS-irrigated sugarcane (*Saccharum officinarum* L.). Field trial data from Okinawa, Japan, spanning three growing seasons (including the main crop and two ratoons), two distinct planting seasons (spring and summer planting), and two different crops were collected to calibrate and validate the newly developed module linking OPSIS with the APSIM engine. We parameterized, calibrated, and validated the APSIM-Sugar model to simulate the growth, yield, water use, and soil moisture dynamics of OPSIS irrigated sugarcane. APSIM-Sugar successfully represented the growth and yield of OPSIS-irrigated sugarcane. However, the simulation of soil moisture dynamics and irrigation water usage fell short of expected standards. Further research is recommended to improve the simulation accuracy of soil water dynamics and irrigation water usage for OPSIS-irrigated sugarcane.

KEYWORDS

**APSIM-sugar model, irrigation water use, Japan, optimized subsurface irrigation system, soil moisture dynamics**

## 1 Introduction

The Optimized Subsurface Irrigation System (OPSIS) is a neoteric subsurface irrigation method with excellent performance, especially when irrigating upland crops growing on soils with low water holding capacity. It recorded the lowest operational irrigation cost for sugarcane (*Saccharum officinarum* L.) compared to other conventional irrigation methods in Okinawa, Japan. During the functioning of OPSIS, water is driven by gravity along perforated pipes, and its movement outward is determined by soil water potential. This outward flow saturates the soil, and the irrigation amount and rate are governed by the equilibrium of water potential. Capillary action due to surface tension causes the water to move upward and increase the moisture content of the soil in the root zone (Gunarathna et al., 2017). The system is remarkable for its ability to eliminate surface runoff and evaporation. Further, it significantly reduces percolation losses, which are common problems in other subsurface irrigation systems (Gunarathna et al., 2017). Because a small solar-powered pump is used to lift water and create a pressure head, and minimum operational activities are required, OPSIS offers the potential to drastically lower the operational costs of irrigation for sugarcane farmers.

Gunarathna et al. (2018), reported the excellent performance of OPSIS compared to sprinkler irrigation for sugarcane cultivation, but suggested further validation of the results through different evaluation methods. A well-calibrated and validated crop model is a time- and resource-saving alternative for developing and evaluating agronomic practices, making it an indispensable tool for research on technological advancement in agriculture (Saseendran et al., 2008; Kephe et al., 2021). Crop models have proven to be valuable tools for optimizing various agricultural practices, such as fertilizer application and irrigation strategies. For instance, Saseendran et al. (2008) and Abd-El-Baki et al. (2017) employed a numerical crop model to identify the optimal irrigation depth for tomato crops. Kundu et al. (1982) used the CORNGRO crop model to determine the optimal levels of soil moisture depletion, replenishment and the timing and amount of irrigation in different growth stages of maize. Mubeen et al. (2016) employed the CERES -Maize model to optimize irrigation conditions. Sena et al. (2014) used the Agricultural Production Systems Simulator (APSIM) to determine optimal planting dates to achieve higher yields and water productivity of rice-wheat cropping systems in India's middle Indo-Gangetic Plain (IGP). Balwinder-Singh et al. (2016) used APSIM model to evaluate the effects of mulching on sowing date and irrigation management of wheat in central Punjab, India. Subash et al. (2014) evaluated the different irrigation systems for rice-wheat cropping systems in the IGP using the APSIM model. Therefore, utilizing crop model simulations could be a valuable approach for assessing the effectiveness of OPSIS.

## 1.1 APSIM

APSIM is an open-source (for noncommercial users) crop modeling software, offers a wide range of capabilities for modeling crop growth and yield of many crops, including sugarcane (Keating et al., 2003; Holzworth et al., 2014). In addition, APSIM provides modeling functionalities to simulate soil water dynamics, and nutrient dynamics (Inman-Bamber and McGlinchey, 2003; Keating et al., 2003; Holzworth et al., 2014; Inman-Bamber et al., 2016). Plant models in APSIM effectively simulate crucial physiological processes such as water and nutrient uptake, phenology, organ development, and responses to abiotic stress. Meanwhile, soil models in APSIM simulate water movement such as infiltration, capillary rise, evapotranspiration, drainage and surface runoff. The simulation of water and solute movement utilizes both a simplified tipping bucket approach by module SOILWAT (Probert et al., 1998), and a comprehensive numerical solution based on Richard's equation by module SWIM (Huth et al., 2012).

One significant advantage of APSIM over other crop modeling software is its ability to integrate complex management measures through scripting languages. This flexibility allows users to customize simulations by incorporating specific farming practices, irrigation schedules, and adaptive management strategies, making it a powerful tool for diverse agricultural applications. As a result, APSIM provides a highly flexible and dynamic platform for simulating real-world agricultural scenarios, improving decision-making and resource management (Archontoulis et al., 2014; Holzworth et al., 2014). It is essential to undertake thorough parameterization, calibration, and validation processes, relying on error statistics derived from experimental data to minimize uncertainties in model predictions. These steps are crucial for reducing uncertainties and ensuring more accurate predictions.

The objective of this research was to enhance the modeling capabilities of APSIM for effectively assessing OPSIS performance. To achieve this, we integrated field experiments with modeling efforts to parameterize and calibrate APSIM, ensuring accurate simulation of the growth and yield of sugarcane under OPSIS irrigation. Furthermore, we conducted extensive field trials alongside modeling work to validate APSIM's predictive capabilities, specifically under the newly implemented OPSIS. To comprehensively assess the accuracy and reliability of APSIM's simulations, we employed a set of model evaluation criteria throughout the calibration and validation phases. This rigorous approach aimed to improve the model's ability to simulate real-world conditions, ultimately enhancing its applicability for OPSIS-irrigated sugarcane systems.

# 2 Materials and methods

To acquire the essential data for parameterization and calibration of the APSIM-Sugar model, we carried out a sequence of field experiments in Itoman, Okinawa, Japan (26° 7′ 59.07" N, 127° 40′ 52.32″E). These experiments specifically focused on the locally cultivated Ni21 sugarcane cultivar which was developed to withstand strong winds from typhoons. The single-row planting method with 1.3 m spacing between rows was used in all treatments. Additionally, we maintained sugarcane fields irrigated with OPSIS to collect the required data for validating the compatibility of APSIM with OPSIS.

## 2.1 Plant data

Two experimental fields were diligently maintained as sprinkler-irrigated and OPSIS-irrigated sugarcane. Detailed information on the field trials are provided by Gunarathna et al. (2018). The data from the sprinkler-irrigated field was utilized for parameterizing and calibrating the APSIM-Sugar model, while the OPSIS-irrigated field served as a means to validate the compatibility of APSIM with OPSIS. According to the local practice in Okinawa, Japan, we conducted field experiments to observe growth and yield under two planting conditions: spring planting and summer planting. Specifically, we conducted spring planting in April 2013, with the harvest taking place in March 2014. Additionally, the cultivation was extended to observe the growth and yield of two consecutive ratoon crops, harvested in January 2015 and January 2016. Furthermore, we initiated summer planting in October 2013, with the harvest occurring in January 2015. For OPSIS irrigation, we exclusively extended it to observe the growth and yield of the first ratoon crop, which was harvested in January 2016.

Following standard fertilization practices in Okinawa, we applied 350 kg/ha of urea fertilizer for both the main crop and ratoon, regardless of the irrigation method. For the sprinkler-irrigated sugarcane, the fertilizer was added 31 and 62 days after planting or harvesting, respectively for main and ratoon crops. Conversely, for OPSIS-irrigated sugarcane, we employed a 10-split application method, applying the same amount of fertilizer during the first 3 months as in the OPSIS implementation.

We randomly selected an area of 5.2 $m^2$ to estimate the yield of fresh sugarcane from the main crops planted in spring and summer and from the two ratoon crops. We also conducted stalk counts per unit area to determine the stalk densities of the different crops at harvest. Though it is uncommon to use plant height for calibrating or validating the APSIM-Sugar model in previous studies, we employed this parameter due to the unavailability of other evaluation parameters. To measure the plant height, we focused on the main crop planted in summer and the first ratoon crop of the spring-planted crop. Monthly measurements were taken from May 2014 to January 2015, using the distance from the soil surface to the +1 dewlap as the indicator of plant height (de Sousa et al., 2015).

## 2.2 Soil data

To estimate various soil properties, we collected soil samples from six distinct layers as 0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm. These samples were utilized to determine lower limit (LL15, mm/mm), drained upper limit (DUL, mm/mm), soil saturation (SAT, mm/mm), saturated hydraulic conductivity (KS, mm/day), particle density (TD, g/$cm^3$), and bulk density (BD, g/$cm^3$). LL15 represents the volumetric water content at equilibrium under −1,500 kPa, while DUL corresponds to the volumetric water content at equilibrium under −33 kPa. To measure these parameters, we employed the centrifuge method (Khanzode et al., 1999; ASTM International, 2003; Vero et al., 2016). The measured values of BD and TD were used in estimating soil saturation. Saturated hydraulic conductivity was determined using the constant-head method (ASTM International, 2003). Additionally, the soil samples were analyzed to determine soil pH, soil carbon, $NO_3^-$-N and $NH_4^+$-N. To reflect the specific soil conditions in Itoman, Okinawa, we created a new soil profile in APSIM and parameterized it using the measured data as presented in Table 1.

To assess the soil moisture dynamics under OPSIS irrigation, soil moisture measurements were taken at various depths of OPSIS irrigated field during first and second ratoon crops of the spring planting. Soil moisture sensors (5TE, Decagon Devices, Pullman, WA, USA) were employed to measure soil moisture levels at depths of 5, 15, 25, 35, 45, and 55 cm.

## 2.3 Irrigation water use

To determine the irrigation water use under the OPSIS, we measured the irrigation input of the first and second ratoon crops of OPSIS-irrigated spring-planting. Flow meter (Aichi Tokei TR-IV) attached to the outlet of the water column and the inlet to the water collecting tank of the OPSIS system were used to estimate the daily amount of irrigation by the OPSIS.

## 2.4 Climatological data

Meteorological data for Naha, Okinawa, Japan, including daily precipitation, maximum and minimum temperatures, radiation, wind speed, relative humidity, and barometric pressure were acquired from the Japan Meteorological Agency.[1] The data covered the timeframe from January 1, 1980, to August 31, 2016. To calculate the annual mean ambient temperature and the annual amplitude of mean monthly temperature, the tav_amp utility software provided by APSIM was used.[2] Using the aforementioned data, a new meteorological file was parameterized.

## 2.5 APSIM-OPSIS module

In APSIM, subsurface irrigation can be practiced with the optional 'depth' argument. The SoilWater module calculates which soil layer this depth corresponds to and applies water directly to that soil layer. This can result in significant percolation losses, but normally OPSIS shows lower percolation losses compared to other subsurface irrigation methods (Gunarathna et al., 2017). So, we developed a new module named "OPSIS" to establish a connection between the OPSIS to the APSIM engine. In this module, the fifth layer (50–60 cm) was designated as the base layer representing the location of OPSIS within the system. The difference between the soil saturation (SAT) and the soil moisture content (SW) of the layer is identified as the irrigation water input for the layer. The

1 www.jma.go.jp/jma/menu/report.html
2 https://www.apsim.info/Products/Utilities

TABLE 1 Parameterized Itoman soil profile based on observed soil data.

| Depth (cm) | Bulk density (g/cc) | KS (mm/day) | SAT (mm/mm) | DUL (mm/mm) | LL15 (mm/mm) | Air dry (mm/mm) | Sugar LL (mm/mm) |
|---|---|---|---|---|---|---|---|
| 0–10 | 1.107 | 7,827 | 0.481 | 0.422 | 0.277 | 0.100 | 0.277 |
| 10–20 | 1.154 | 19,712 | 0.48 | 0.415 | 0.295 | 0.100 | 0.295 |
| 20–30 | 1.310 | 10,834 | 0.484 | 0.453 | 0.298 | 0.100 | 0.298 |
| 30–40 | 1.197 | 4,432 | 0.496 | 0.447 | 0.300 | 0.100 | 0.300 |
| 40–50 | 1.237 | 814 | 0.511 | 0.436 | 0.310 | 0.100 | 0.310 |
| 50–60 | 1.264 | 800 | 0.522 | | 0.290 | 0.100 | 0.290 |

estimated irrigation amount by the OPSIS is referred to as "opsis (mm/day)."

## 2.6 APSIM simulation

APSIM, is a process-based dynamic crop model that integrates biophysical and management modules into a central engine to simulate different cropping systems (Keating et al., 2003; Holzworth et al., 2014). By leveraging daily weather data as inputs, APSIM can simulate key processes, including crop growth, development, yield, and interactions with the soil, providing a comprehensive framework for agricultural system analysis. The APSIM 7.10 sugar model was first modified to incorporate a new cultivar Ni21. Subsequently, we carried out a detailed parameterization process to accurately represent the growth characteristics of Ni21 within the model. This process involved integrating data from multiple sources, including field measurements, published studies and reports specifically focused on the Ni21 cultivar., and expert knowledge from agronomists and researchers. By synthesizing these diverse data inputs, we were able to establish the key cultivar parameters required for accurate simulation, which are detailed in Table 2. This comprehensive approach ensured that the model could reliably capture the growth, yield, and physiological responses of Ni21 under varying environmental and management conditions.

Then, we conducted simulations to evaluate the growth and yield of sugarcane crops that were planted in both spring and summer seasons and subjected to sprinkler irrigation. The simulation period spanned from March 2013 to January 2016 for the spring-planted crop and from September 2013 to January 2015 for the summer-planted crop. However, we observed that APSIM underestimated the growth and yield.

TABLE 2 Ni21 Cultivar and sugarcane plant-specific parameters used to parametrization and calibration of APSIM-Sugar model.

| Parameter (Description, units) | Initial values (parameterization) | | Values used for simulations (after calibration) | |
|---|---|---|---|---|
| | Crop | Ratoon | Crop | Ratoon |
| Leaf_size (Leaf area of the respective leaf, $mm^2$) | | | | |
| Leaf No.: 01 | 2000 | 2000 | 2000 | 2000 |
| Leaf No.: 14 | 48,000 | 48,000 | 48,000 | 48,000 |
| Leaf No.: 20 | 48,000 | 48,000 | 48,000 | 48,000 |
| Crop_height_max (Maximum crop height, mm) | 6,000 | 6,000 | 4,000 | 4,000 |
| cane_fraction (Fraction of accumulated biomass partitioned to cane, $gg^{-1}$) | 0.7 | 0.65 | 0.7 | 0.7 |
| tt_emerg_to_begcane (Accumulated thermal time from emergence to beginning of cane, °C day) | 1800 | 1800 | 1900 | 1900 |
| tt_begcane_to_flowering (Accumulated thermal time from beginning of cane to flowering, °C day) | 6,000 | 6,000 | 6,000 | 6,000 |
| tt_flowering_to_crop_end (Accumulated thermal time from flowering to end of the crop, °C day) | 2000 | 2000 | 2000 | 2000 |
| Sucrose_fraction_stalk (Fraction of accumulated biomass partitioned to sucrose, $gg^{-1}$) | | | | |
| Stress factor: 0.2 | 1.0 | 1.0 | 1.0 | 1.0 |
| Stress factor: 1 | 0.5 | 0.5 | 0.5 | 0.5 |
| sucrose_delay (Sucrose accumulation delay, $gm^{-2}$) | 0 | 0 | 0 | 0 |
| min_sstem_sucrose (Minimum stem biomass before partitioning to sucrose commences, $gm^{-2}$) | 800 | 800 | 800 | 800 |
| min_sstem_sucrose_redn (Reduction to minimum stem sucrose under stress, $gm^{-2}$) | 10 | 10 | 10 | 10 |
| green_leaf_no (Maximum number of fully expanded green leaves, No.) | 13 | 13 | 13 | 13 |
| Tillerf_leaf_size (Tillering factors according to the leaf numbers, $mm^2$ $mm^{-2}$) | | | | |
| Tiller_leaf_size_no = 1 | 1.5 | 1.5 | 1.5 | 1.5 |
| Tiller_leaf_size_no = 4 | 1.5 | 1.5 | 1.5 | 1.5 |
| Tiller_leaf_size_no = 10 | 1.5 | 1.5 | 1.5 | 1.5 |
| Tiller_leaf_size_no = 16 | 1 | 1 | 1 | 1 |
| RUE (Radiation use efficiency, g/MJ) | | | | |
| Stage code = 1 | 0 | 0 | 0 | 0 |
| Stage code = 2 | 0 | 0 | 0 | 0 |
| Stage code = 3 | 1.80 | 1.65 | 2.00 | 1.85 |
| Stage code = 4 | 1.80 | 1.65 | 2.00 | 1.85 |
| Stage code = 5 | 1.80 | 1.65 | 2.00 | 1.85 |
| Stage code = 6 | 0 | 0 | 0 | 0 |

To address this issue, we made modifications to the Radiation Use Efficiency (RUE) parameter based on the recommendations proposed by Gunarathna et al. (2019) and Sexton et al. (2017). Additionally, Dias and Sentelhas (2017) and Dias et al. (2019) proposed significant changes to enhance APSIM-Sugar's ability to simulate the growth and yield of Brazilian sugarcane genotypes. We adjusted the maximum RUE values to a maximum of 2.0, aligning with the findings of Muchow et al. (1997) and de Silva and Costa (2012). Similarly, for the ratoon crop, we increased the maximum RUE values to 1.85, consistent with the gap identified by APSIM. Given that the Ni21 cultivar is designed to withstand typhoons, it typically exhibits limited plant height growth. Consequently, we restricted the maximum plant height to 4,000 mm, deviating from the default setting of 6,000 mm. Furthermore, we calibrated the cane fraction (CF) and thermal time from emergence to the beginning of the cane (EB) by employing a trial-and-error approach to determine the optimal values for these parameters (Table 2).

Subsequently, we proceeded to simulate the growth and yield of sugarcane crops planted in the spring (spanning from March 2013 to January 2016) and summer (from September 2013 to January 2016) using the OPSIS. We employed various parameters for validation purposes, including the fresh cane weight at harvest, plant heights of the first ratoon in the spring crop, plant heights of the main crop in the summer crop, soil moisture in the top five soil layers, and the amount of water utilized for irrigation by OPSIS to validate the use of APSIM in conjunction with OPSIS.

During the summer of 2015, a series of typhoons occurred, resulting in substantial crop damage. To account for this impact, we adjusted the observed yields of the second ratoon in the spring crops (for both sprinkler and OPSIS irrigation) and the first ratoon in the summer crops. After careful consideration of field observations, historical yield records, and expert opinions, we supplemented the observed yields with an additional 20% of the recorded yield.

## 2.7 Model evaluation

To assess the accuracy of the simulations, we employed various model evaluation criteria (Krause et al., 2005; Dias and Sentelhas, 2017), including root mean square error (*RMSE*; Equation 1), mean absolute error (*MAE*; Equation 2), coefficient of determination ($R^2$; Equation 3), and Wilmott's agreement index (*d*; Equation 4) (Willmott, 1981). Lower values of *RMSE* and *MAE* indicate a better agreement between the model outputs and observed values. Similarly, higher values of $R^2$ and *d* signify a stronger level of agreement. Additionally, we utilized Lin's concordance correlation coefficient (*CCC*) (Ojeda et al., 2017), which combines precision through Pearson's correlation coefficient and accuracy through bias. The CCC integrates both measures to evaluate how closely the regression line aligns with the concordance line which is 45° line through the origin. The *CCC* ranges from −1 to 1, with perfect agreement indicated by a value of 1. Notably, the *CCC* allows for accurate assessment even with limited observations, as it considers the continuous measure obtained from two methods, as highlighted by Ojeda et al. (2017). We calculated the *CCC* using the epiR package (Stevenson et al., 2018) within the R software environment (R Core Team, 2018).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(S_i - O_i\right)^2} \tag{1}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|S_i - O_i\right| \tag{2}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)\left(S_i - \bar{S}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}\sqrt{\sum_{i=1}^{n}\left(S_i - \bar{S}\right)^2}}\right]^2 \tag{3}$$

$$d = 1 - \frac{\sum_{i=1}^{n}\left(S_i - O_i\right)^2}{\sum_{i=1}^{n}\left(\left|S_i - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)^2} \tag{4}$$

where, $n$ is the number of observations, $S_i$ and $O_i$ are the simulated and observed value of the respective parameter fresh cane yield (t/ha), plant height (mm), soil moisture (mm/mm), irrigation water (mm/month) respectively; and $\bar{O}$ and $\bar{S}$ are the average of simulated and observed values, respectively.

# 3 Results and discussion

## 3.1 Parameterization and calibration of APSIM-sugar to simulate growth and yield of cultivar Ni21

The APSIM-Sugar model was updated by incorporating the new cultivar Ni21 into the XML file. We utilized a combination of field measurements (leaf size and number of green leaves), information from published reports, and expert opinions to parameterize this cultivar parameters (Table 2). After implementing the Ni21 cultivar to the APSIM-Sugar model, we conducted simulations to estimate the fresh cane weight and plant height. Initially, the simulations showed moderate agreement between the observed values and the simulated results. However, it was observed that APSIM underestimated the fresh cane weight. To address this issue, we made adjustments to the plant parameters, specifically the maximum radiation use efficiency (RUE) and maximum plant height for both the main and ratoon crops referring to the literature (Muchow et al., 1997; de Silva and Costa, 2012). Additionally, we performed calibration for certain cultivar parameters, namely cane fraction (CF) and thermal time from emergence to the beginning of the cane (EB). The calibration process involved iterative adjustments to find optimal values for these parameters. The resulting simulations, incorporating the modified plant parameters and calibrated cultivar parameters, demonstrated improved relationships between the simulated outcomes and the observed values, as depicted in Figure 1.

The APSIM-Sugar model has proven to be capable of simulating accurate results that align well with observations of cane and sucrose yields, despite the inherent variability influenced by planting season, nutrient conditions, weather conditions, and other undefined factors (Keating et al., 1999; Cheeroo-Nayamuth et al., 2000; Inman-Bamber and McGlinchey, 2003; Inman-Bamber et al., 2016).

In a study conducted by Keating et al. (1999), the performance of the APSIM-Sugar model was evaluated using data sets from various cultivars grown in different locations. The results of the study indicated that the model exhibited a relatively high level of accuracy in simulating millable stalk weight as $R^2$ and the root mean square deviation (*RMSD*) demonstrated a satisfactory value of 0.72 and 1.94 t/ha, respectively. A study conducted by Inman-Bamber et al. (2016) demonstrated the improved predictive ability of the APSIM-Sugar model by incorporating modifications related to transpiration efficiency and root water supply. The researchers recognized the importance of specific modifications to enhance the model performances and accuracy. These findings provide evidence for the capability of the APSIM-Sugar model to accurately capture and simulate the growth and yield parameters of sugarcane.

Our study further confirms the capability of the APSIM-Sugar model to accurately simulate fresh cane weight and plant height. The evaluation of the model using various criteria demonstrates the strong agreement between the simulated results and the observed data. For the simulation of fresh cane weight, the *RMSE* was found to be 3.195 t/ha, indicating a relatively small deviation between the model's predictions and the actual observations. The $R^2$ value of 0.93 suggests a high level of correlation between the simulated and observed values. Additionally, the *MAE* of 2.74 t/ha signifies the average magnitude of the differences between the simulated and observed fresh cane weights. Similarly, the simulations of plant height also exhibited a good level of agreement with the observed values. The *RMSE* value of 493 mm indicates a relatively small discrepancy between the model's predictions and the actual plant heights. The $R^2$ value of 0.87 indicates a strong correlation between the simulated and observed plant heights. Furthermore, the *MAE* value of 397 mm represents the average magnitude of the differences between the simulated and observed plant heights. These evaluation criteria collectively support the conclusion that the APSIM-Sugar model performs well in accurately simulating fresh cane weight and plant height, providing reliable estimates that align closely with the observed data.

In this study, we deviated from the commonly used maximum values of RUE in APSIM crop modeling. Our aim was to minimize the disparity between the simulated and observed values under high input conditions with new genotypes. While it is not a conventional approach in APSIM modeling studies, we adjusted the maximum RUE values. It is worth noting that APSIM typically considers factors such as soil moisture status, nutrient availability, and the phenomenon of reduced growth (RGP) when determining RUE values (Park et al., 2005). RGP occurs when extremely favorable environmental conditions can lead to lodging, resulting in a reduction in RUE (Park et al., 2005; van Heerden et al., 2015).

## 3.2 Validation of APSIM to simulate growth and yield of cultivar Ni21 under OPSIS

Using the newly parameterized and calibrated APSIM-Sugar model and APSIM-OPSIS module, we conducted simulations of fresh cane weight and plant height for the Ni21 sugarcane cultivar under OPSIS. The simulation results exhibited a favorable agreement with the observed values for fresh cane yield and plant height. Additionally, the observed soil moisture dynamics and irrigation water use demonstrated acceptable agreement with the simulated values.

### 3.2.1 Plant height

For sugarcane planted in summer, the APSIM model combined with OPSIS demonstrated satisfactory simulation results for plant height (Figure 2). While there was a slight underestimation in the later stages of the crop, the model evaluation criteria indicated a close match between the simulations and observations (Table 3). In contrast, the first ratoon of the spring-planted crop exhibited some

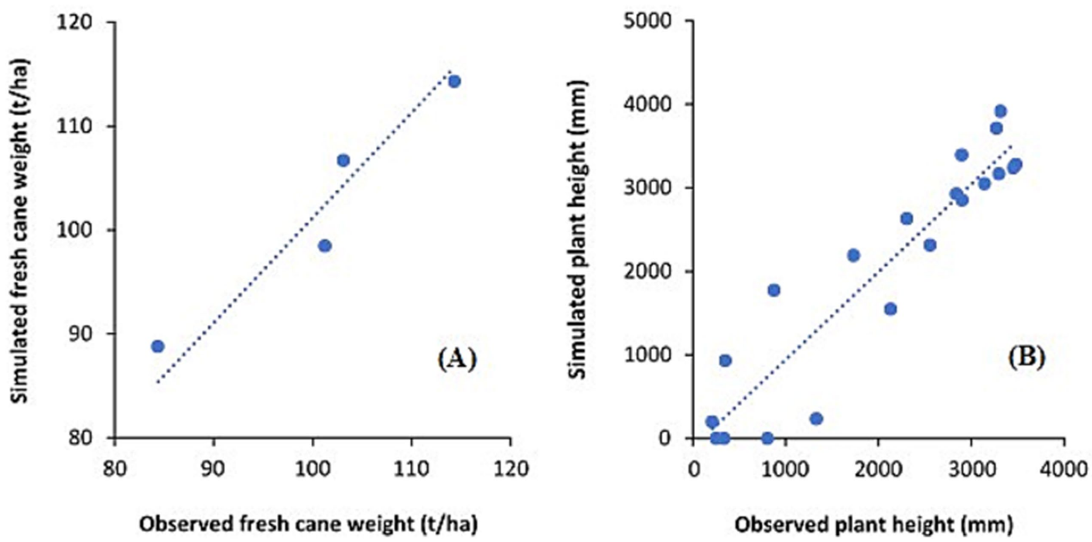


FIGURE 1
Observed versus simulated **(A)** fresh cane weight, and **(B)** plant height of sugarcane cultivar Ni21.

discrepancies between the observed and simulated plant heights. APSIM-Sugar simulated lower plant heights during the early stages, but showed a higher growth rate in the later stages compared to the observed data (Figure 3). Consequently, the simulated plant height at harvest was slightly higher (4%) than the observed value. Although the simulation accuracy for the first ratoon of the spring crop is not as precise as the summer plant, the model evaluation criteria still indicate a reasonable agreement with the observations (Table 3). Moreover, Table 3 confirms that the simulation of plant height for the summer-planted main crop outperforms the results of the calibration study, while the first ratoon crop of the spring-planted crop exhibits slightly weaker performance compared to the calibration results.

### 3.2.2 Fresh cane weight

Confirming the proficiency of APSIM in simulating fresh cane weight, the APSIM model with OPSIS successfully simulated fresh cane yield exhibiting good agreement with the observed values (Figure 4). The model evaluation criteria further support this agreement, with all criteria indicating a favorable correspondence between the simulations and observations (Table 3). The reported *RMSE* value (6.08 t/ha) is considered satisfactory, representing approximately 5% of the average observed fresh cane yield. $R^2$ (0.82) and d (0.64) provide additional confirmation of the reasonable agreement between the observed and simulated fresh cane yield. Notably, these validation results are on par with the outcomes of the calibration study. Likewise, a previous study by Mao et al. (2018) showcased the high accuracy of locally calibrated APSIM-Sugar in simulating cane yield.

### 3.2.3 Soil moisture dynamics

Figure 5 depicts the observed and simulated variations in soil moisture across different soil layers during the first and second ratoons of spring planting. The simulation results reveal that APSIM tends to overestimate soil moisture levels, particularly in the upper portion of the root zone. This discrepancy may be attributed to the complex nature of soil water movement, which presents a challenge for simplified modeling approaches to accurately capture it. In this study, a cascading layer approach was employed to estimate soil water movement. While this method offers a structured way to simulate moisture dynamics, it may not fully account for the intricate processes governing soil water retention, infiltration, and redistribution. As a result, the overestimation observed in the upper soil layers suggests potential limitations in APSIM's ability to precisely model surface moisture interactions. Our findings align with previous studies, which have also reported similar trends in APSIM's soil moisture simulations. For instance, Balwinder-Singh et al. (2011) noted that APSIM generally overestimates soil moisture in the upper layers while providing reasonable accuracy in the lower soil strata. Another crop simulation study conducted by Marin et al. (2011) demonstrated fairly accurate simulation of soil water content using the calibrated DSSAT/Canegro model, with a mean *RMSE* of 0.214 mm. Additionally, Archontoulis et al. (2014) highlighted the ability of APSIM to simulate soil water dynamics with good accuracy, reporting an *RMSE* of 0.032 mm/mm in their predictions. Sena et al. (2014) observed significant discrepancies between observed and simulated soil moisture levels. However, they successfully minimized these errors by calibrating soil parameters, underscoring the importance of model refinement in improving simulation accuracy. These findings emphasize the need for further refinement of APSIM's soil water modeling, particularly in the upper layers, to enhance its predictive accuracy. Future research could explore alternative approaches, such as integrating more advanced soil water movement algorithms or improving parameter calibration, to better capture the complexities of soil moisture dynamics in varying environmental and management conditions.

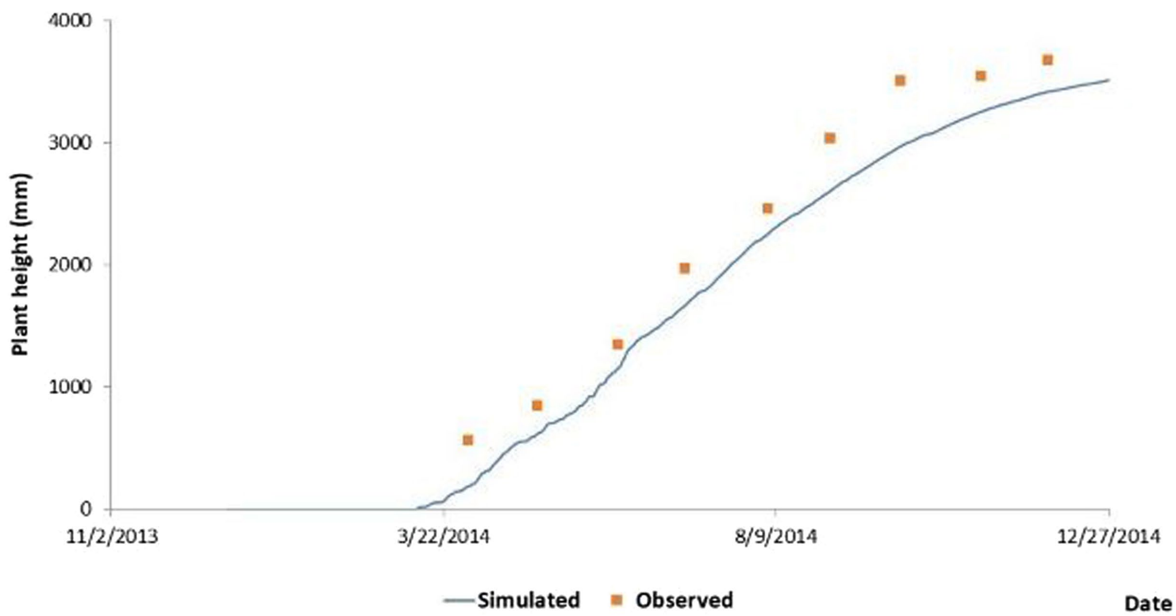


FIGURE 2
Observed and simulated plant height of sugarcane (summer planted main crop).

TABLE 3 Evaluation of simulation accuracy of APSIM combined with OPSIS module.

| Variable (unit) | Planting season (Crop/ratoon) | Model evaluation criterion | | | | |
|---|---|---|---|---|---|---|
| | | $R^2$ | *RMSE | *MAE | d | CCC |
| Fresh cane yield (t/ha) | All | 0.82 | 6.08 | 4.67 | 0.64 | 0.56 |
| Plant height (mm) | Summer plant (Crop) | 0.99 | 306 | 286 | 0.98 | 0.97 |
| | Spring plant (1st ratoon) | 0.96 | 769 | 582 | 0.91 | 0.85 |
| Monthly irrigation water use (mm/month) | Spring plant (1st ratoon) | 0.01 | 13.18 | 11.19 | 0.47 | 0.07 |
| | Spring plant (2nd ratoon) | 0.22 | 17.45 | 15.51 | 0.27 | 0.39 |
| Average soil moisture of root zone (mm/mm) | Spring plant (1st ratoon) | 0.32 | 0.052 | 0.047 | 0.49 | 0.16 |
| | Spring plant (2nd ratoon) | 0.50 | 0.056 | 0.053 | 0.45 | 0.15 |

*Unit is equal to the unit of the variable.

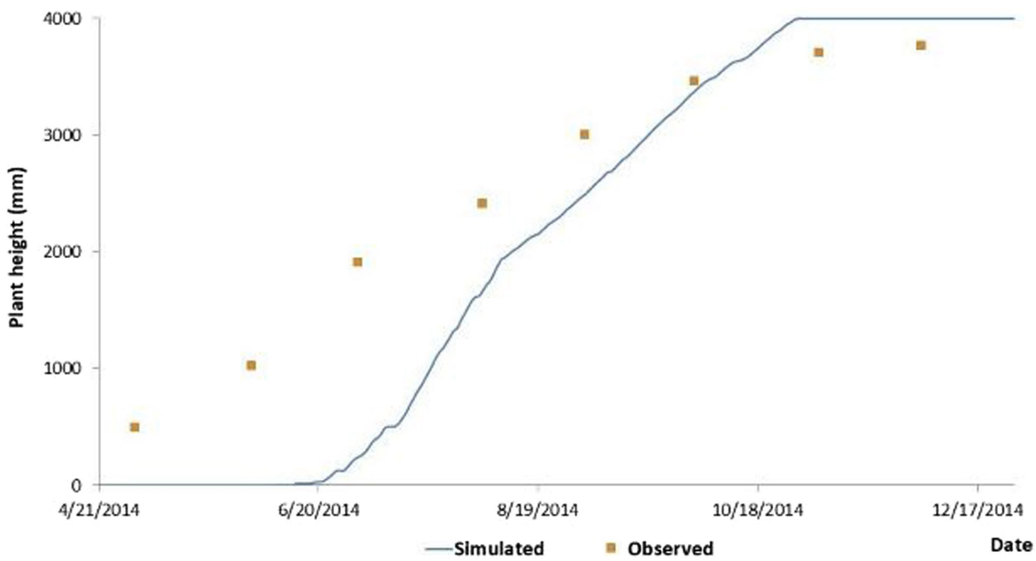


FIGURE 3
Observed and simulated plant height of sugarcane (spring planted first ratoon crop).

The SOILWAT module demonstrated reasonably accurate predictions of soil water dynamics in the OPSIS-operated sugarcane fields. However, the observed overestimation of soil moisture in the upper soil layers suggests potential discrepancies between the simulated and actual daily rates of soil evaporation, capillary rise, and the effects of the saturated flow parameter (SWCON) on lower downdrafts. These inconsistencies highlight the need for further investigation to better understand the underlying causes of these deviations and refine the model for improved accuracy. Accurately modeling bottom water dynamics requires a comprehensive study with detailed field measurements to capture the complex interactions governing water movement within the soil profile. Without precise data, it remains challenging to enhance the simulation of key hydrological processes such as drainage, infiltration, and capillary rise in subsurface irrigation systems. Brown et al. (2018) have proposed a comprehensive model (WEIRDO, Water Evapotranspiration Infiltration Redistribution Drainage runOff) which offers a more sophisticated framework for simulating soil water dynamics. WEIRDO incorporates a broader range of hydrological processes and may provide a more accurate representation of soil moisture behavior. However, it is specifically designed for use with the APSIM next-generation model, whereas our study utilized the classic version of APSIM (APSIM 7.10), rendering the use of WEIRDO unfeasible in our current study. Nonetheless, given the potential of the WEIRDO model to capture the complexities of soil moisture dynamics in OPSIS-irrigated fields, we recommend investigating its applicability in future studies. Incorporating such advanced modeling approaches may enhance the predictive accuracy of APSIM, particularly in subsurface irrigation systems, leading to improved water management strategies and optimized irrigation practices.

### 3.2.4 Irrigation water use

Figure 6 shows the relationship between observed and simulated irrigation water volume (irrigated as OPSIS) during the first ratoon crop of spring-planting. As with soil moisture, APSIM over-predicted irrigation water use by OPSIS.

It is worth noting that there are no existing studies comparing irrigation water use because APSIM typically does not simulate irrigation volume. In our study, we simulated irrigation water use for a newly developed irrigation system, OPSIS. The model evaluation

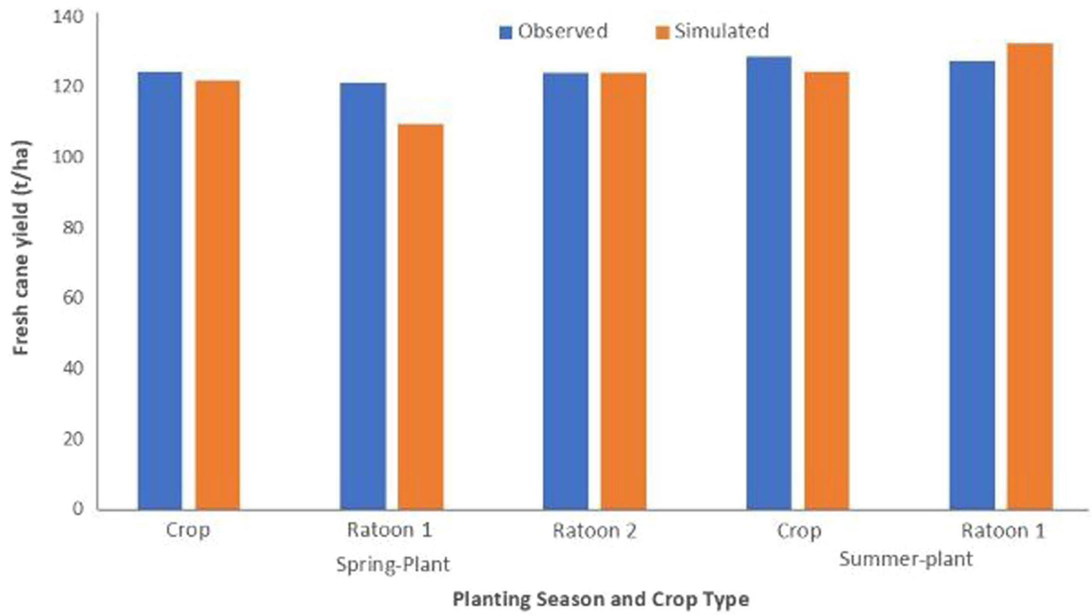


FIGURE 4
Comparison of observed and simulated yield of sugarcane with OPSIS.

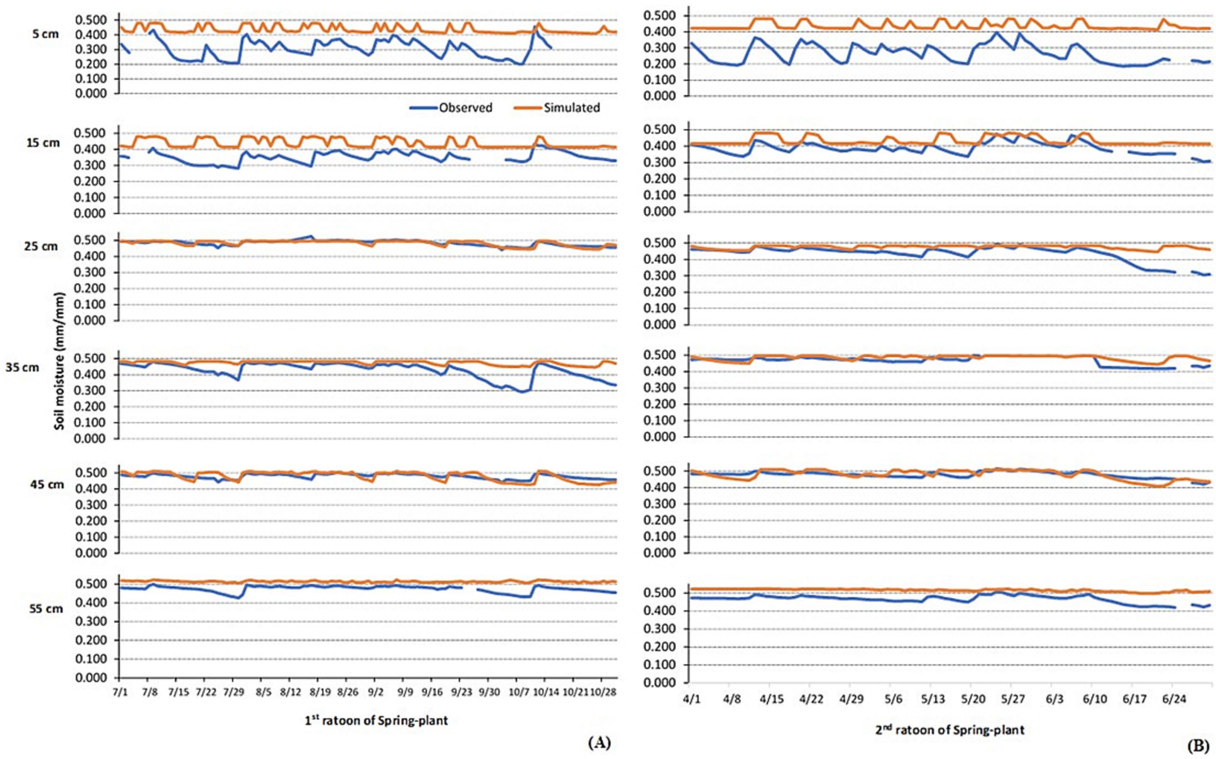


FIGURE 5
Observed and simulated soil moisture variation in different layers of the soil **(A)** during the first and **(B)** second ratoon crop of the spring planting.

criteria presented in Table 3 indicate that the simulation results for irrigation volume are not in close agreement with the observed values. However, the *MAE* values indicate that the estimated errors are 11.2 and 15.5 mm/month for the first and second-ratoon crops, respectively. The use of a comprehensive soil moisture dynamics simulation model could potentially improve the accuracy of irrigation volume predictions. This is because irrigation water use is influenced by factors such as crop water requirements and losses due to soil

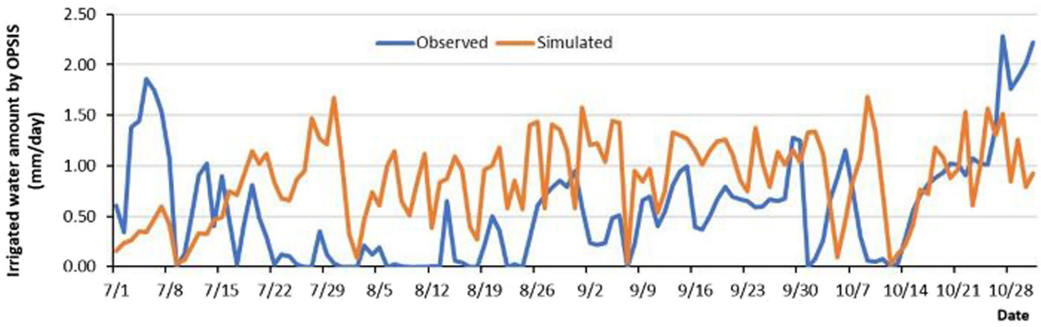


FIGURE 6
Observed and simulated irrigation water use through the OPSIS (spring-planted first ratoon crop).

evaporation and percolation. Further research and development in this area could help refine the irrigation volume estimations.

## 4 Conclusions and recommendations

In this study, we made modifications to the APSIM-Sugar model to accurately simulate the growth and yield of sugarcane cultivar Ni21 in Japan. To achieve this, we parameterized the cultivar using a combination of measured values, information from published reports, and expert opinions. However, when applied to Okinawan conditions, the initial APSIM simulations underestimated the growth and yield of the Ni21 cultivar. Consequently, we proceeded to modify and calibrate the APSIM-Sugar model by focusing on key factors such as radiation use efficiency, thermal time from emergence to the beginning of cane, and cane fraction. Through calibration, we were able to establish a close correspondence between the APSIM simulations and the observed data. In order to further validate the use of APSIM with OPSIS, we developed the APSIM-OPSIS module, which serves as an interface between OPSIS and the APSIM engine. The simulation results obtained using APSIM-OPSIS demonstrated good agreement with the observed data. Specifically, both plant height and fresh cane yield were accurately simulated and exhibited close agreement with the observations. However, it is worth noting that APSIM displayed a tendency to overestimate soil water content in the upper layers of the soil profile, as well as the irrigation water use of OPSIS. These discrepancies in soil water content and irrigation water use will require further investigation and refinement to enhance the accuracy of the simulations.

The APSIM-OPSIS module, developed for simulating sugarcane growth and yield in conjunction with an optimized subsurface irrigation system, has demonstrated its effectiveness in achieving successful simulations. The results obtained from APSIM-OPSIS show good agreement with observed data, indicating its capability to capture the dynamics of sugarcane development under OPSIS. However, there is room for improvement in terms of accurately simulating soil water dynamics and estimating irrigation water consumption within the OPSIS system. It is recommended to conduct further studies to enhance the simulation accuracy in these aspects. This could involve refining the algorithms and parameters related to soil water movement, evaporation rates, and the interactions between the irrigation system and soil moisture dynamics. Through additional research and necessary improvements, it is expected that APSIM-OPSIS can be further optimized to provide more accurate simulations of soil water dynamics and irrigation water usage. This would enhance its utility in assessing and optimizing the performance of the OPSIS system for sugarcane cultivation.

## Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Authors acknowledge the ownership of experimental data of Itoman field research carried out by Paddy Research CO., LTD, Land Improvement District, and the University of the Ryukyus. Requests to access these datasets should be directed to janaka78@agri.rjt.ac.lk.

## Author contributions

MHJPG: Conceptualization, Formal analysis, Validation, Writing – original draft, Writing – review & editing. MKNK: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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