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ORIGINAL PAPER

Modelling water fluxes to improve banana irrigation scheduling and management in Magdalena, Colombia

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Abstract

In this paper, an irrigation scheduling model for banana (*Musa* sp.) was developed to simulate crop growth and water fluxes under typical commercial plantation conditions. Whilst generic models exist for scheduling irrigation for many crops, their suitability for bananas are limited because of the asynchronous nature of crop growth. Individual fields on banana plantations typically contain trees at varying stages in their development cycle, so it is important for scheduling to account for this heterogeneity in simulating crop production. A crop modelling approach was developed using field data from Magdalena, an economically important region of banana production in Colombia. Following model development and calibration, irrigation water demand was estimated and weekly irrigation scheduling advice then transmitted by SMS to individual farmers in the region. The model also takes into account farmer feedback on actual irrigation practices to compare against estimated irrigation demands and to train model performance. Despite good model calibration, analysis of irrigation practices from farmer feedback showed only moderate to poor correlation between actual irrigation applications and the scheduling guidance. This implies a reluctance of farmers to change long-established traditional irrigation management practices, despite awareness of the impacts of systematic over-irrigation on yields and increased nutrient leaching risks. Significant ongoing research efforts will be needed to support improved knowledge and practical water management for key plantation crops.

Introduction

Banana (*Musa* sp.) is a fruit crop with significant global production (127.3 million tonnes) and ranked fourth in terms of commodity value (US$ 63.6 billion) after rice, wheat and milk (Ploetz et al. 2015; FAOSTAT 2018). It is also an important commodity crop for income generation and rural employment for millions of households, and a significant source of foreign currency for countries such as Ecuador, Philippines, Costa Rica and Colombia (Panigrahi et al. 2021). Bananas have a high demand for water with supplemental irrigation used to maximise yield (Kumaran and Muthuvel 2009; Pawar et al. 2017). The role of water management in plant growth and fruit yield is widely acknowledged in many crops including banana (Carr 2009), with water cited as being probably the most limiting non-biological factor affecting production (Turner 1995). Indeed, water scarcity during critical growth periods is one of the major factors responsible for low yields (Panigrahi et al. 2019) with limitations in water availability causing yield reductions of up to 65% where annual rainfall is <1100 mm (van Asten et al. 2011).

Numerous models have been developed to support irrigation scheduling for a wide variety of crop types which are potentially suitable for banana (Leib et al. 2001; Wang et al. 2017; Simionesei et al. 2020). From a theoretical point of view, whilst these models often work well for different crops they usually provide inaccurate results when specialised applications are sought. There are various reasons why such models are not transferable to other crops including the existence of heterogeneous crop operations, inadequate representation of irrigation infrastructure or soil and cropping characteristics being inadequately defined. Other specific requirements for modelling banana include the need to account for rainfall interception (Turner 1995) which is not usually addressed in broad-spectrum models. There is also still much uncertainty regarding banana crop coefficients with different values reported in the literature (see

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for example Lu et al. 2002; Bassoi et al. 2004; Montenegro et al. 2008) for tropical environments, suggesting that crop coefficients are region specific (Turner 1995). Similarly, van Vosselen et al. (2005) observed complications regarding parameter characterisation using the SWAP model for estimating water use in banana crops.

There are no known studies that have simulated banana irrigation scheduling and management practices. We focused on Colombia, the world's fourth largest exporter responsible for one sixth of global banana exports. The majority of production is concentrated in north west Colombia, with 18% cultivated in the Magdalena and La Guajira regions (ASBAMA 2017). Whilst bananas are often grown on plantations by large agribusinesses, production is also valuable to smallholder farmers who constitute approximately 75% of producers in the Magdalena region (Villalobos 2008). Small-scale banana production relies on high labour inputs, in contrast to high levels of automation in other commodity sectors. In addition, Colombia is vulnerable to water scarcity due to the incidence of droughts caused by El Nino (Ruiz and Pabon 2013; Loboguerrero et al. 2018).

Within the context of a broader study to improve agronomic management practices in Colombian banana production, the aim of this study was to conceptualise and develop a model to simulate crop growth and development, soil water fluxes and irrigation water requirements within a typical banana plantation, and to evaluate the model's suitability to provide weekly irrigation scheduling advice to smallholders.

Materials and methods

Different approaches were used to gather field data for modelling. First, a farmer survey was used to collect relevant data via field visits and semi-structured telephone and/or online interviews. Key contacts engaged in providing agronomy services and crop management support (agronomists, field technicians) to farmers in the Magdalena region were also interviewed. This was complemented by a synthesis of science and grey literature. Local agroclimate information was then used to identify suitable sites for installation of a network of weather stations and in situ soil moisture sensors. A conceptual workflow was developed drawing on available information from the field data and literature to produce a region-specific model for delivering weekly irrigation scheduling guidance across the Magdalena region. A description of the study site, the conceptual workflow for model development, data collection and model calibration are provided below.

Study site

The banana region in Magdalena, Colombia, covers approximately 1167 km^2 and is located between 11°14′31″ N latitude and 74°12′19″ W longitude (Fig. 1). Elevations across the area vary from 6 m near Santa Marta city to approximately 110 m along the eastern boundary of the banana region. The climate is tropical with an average temperature of 29.4 °C and average rainfall of 1500 mm $year^{-1}$. There are distinct rainy (September–October to April–May) and dry (April–May to September–October) seasons. The soils are alluvial and suitable for banana with crops typically planted once and then grown for many years by selecting successive suckers each year, in a process known as ratooning.

Conceptual workflow

A conceptual workflow was used to define data requirements (inputs), modelling components and key outputs (Fig. 2). Input data included climate, soils, cropping and agronomic management data. Region specific climate data were collected from a network of five commercial plantations including two reference sites (Neerlandia and La Victoria) and three other sites (Remanso, Maranón, and Porvenir). We observed during the initial project stages some connectivity issues for the weather stations except for the Neerlandia site. This forced us to define a strategy that would enable the model to be driven by weather data from only the Neerlandia site on occasions when connectivity to the other sites was lost. This was achieved by deriving regression fitting functions to estimate the data for the remaining four stations from the Neerlandia weather station. In addition, we used historical weather data over a longer period (2013–2019) from a local station (Rio Frio) to predict short-term weather trends.

A water balance modelling approach was used to simulate banana irrigation demand on a daily time-step. Once the model was developed, we defined the parameters for calibration and the procedure for fitting the model parameters. After the calibration phase, we delivered weekly irrigation scheduling guidance via a bespoke SMS service to a subset of farmers in the region to assess the utility of the model for supporting improvements in banana irrigation water management.

Field data collection

Five automatic weather stations (Delta-T and iMetos) were installed on selected banana plantations to collect daily weather data including precipitation (P) and the variables to estimate reference evapotranspiration (ETo) based on

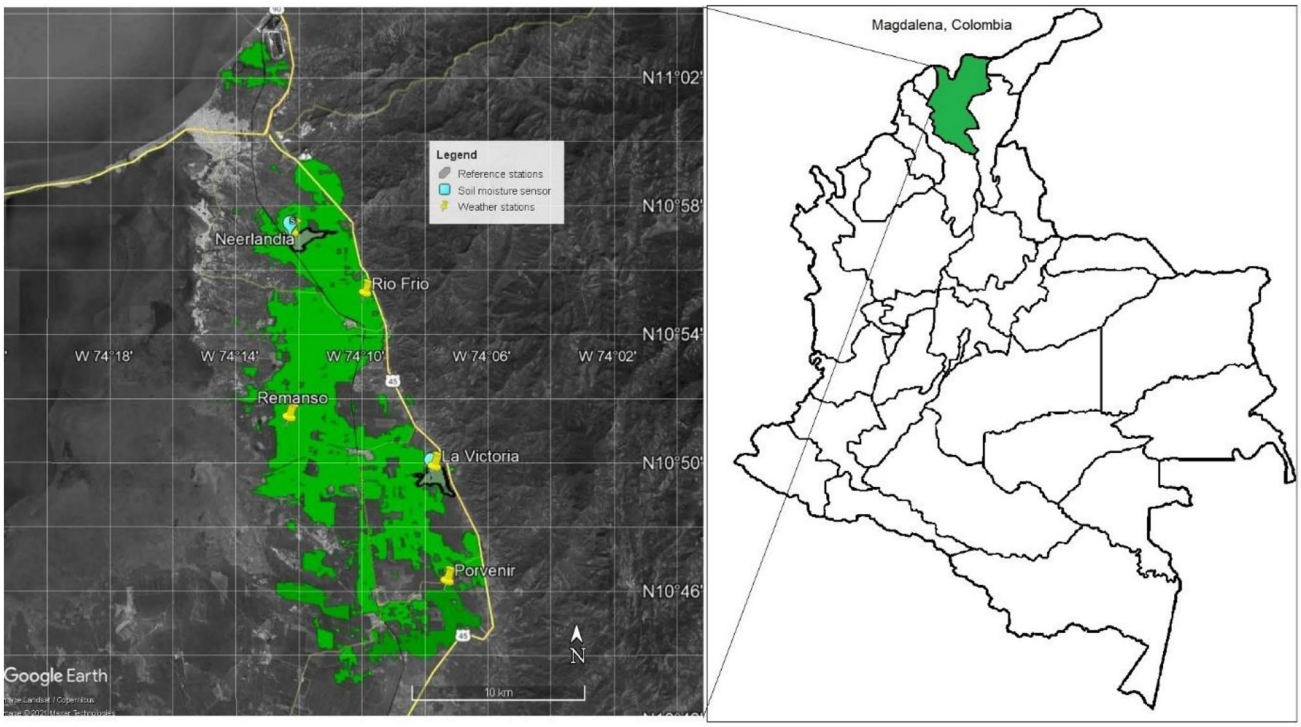


Fig. 1 Banana growing region in Magdalena, Colombia with reference weather stations (those located at Neerlandia and La Victoria), additional weather stations (located at Remanso, Maranón, and Porvenir) and the soil moisture monitoring sites indicated

the Penman–Monteith method at Neerlandia, La Victoria, Remanso, Porvenir and Maranón (Fig. 1). Data from the Delta-T and iMetos stations were received via DeltaLink and FieldClimate cloud services. In addition to the daily updated weather data, a look-up table with historical weather data from 2013 to 2019 were stored from the Rio Frío site and used for weekly weather forecasting. We used the data from Rio Frio to predict weekly weather evolution to perform farmers' irrigation recommendations leveraging the amount of data available.

Two Delta-T (SM150T) soil moisture sensor arrays were installed at two sites; each had nine sensors with three sensors installed at three depths (0.2 m, 0.4 m and 0.6 m) to represent the effective rooting zone for banana. The two sites were the reference site at Neerlandia plus La Victoria. In addition, fieldwork was conducted to determine the soil physical properties (soil texture) to classify the soil characteristics at each site using the method of Carsel and Parrish (1988). We also mapped the location of all smallholder banana farmers in the region and allocated the nearest weather station to each farm.

Development of the simulation model

A water balance model based on Eqs. 1, 2 and 3 was defined to estimate irrigation needs:

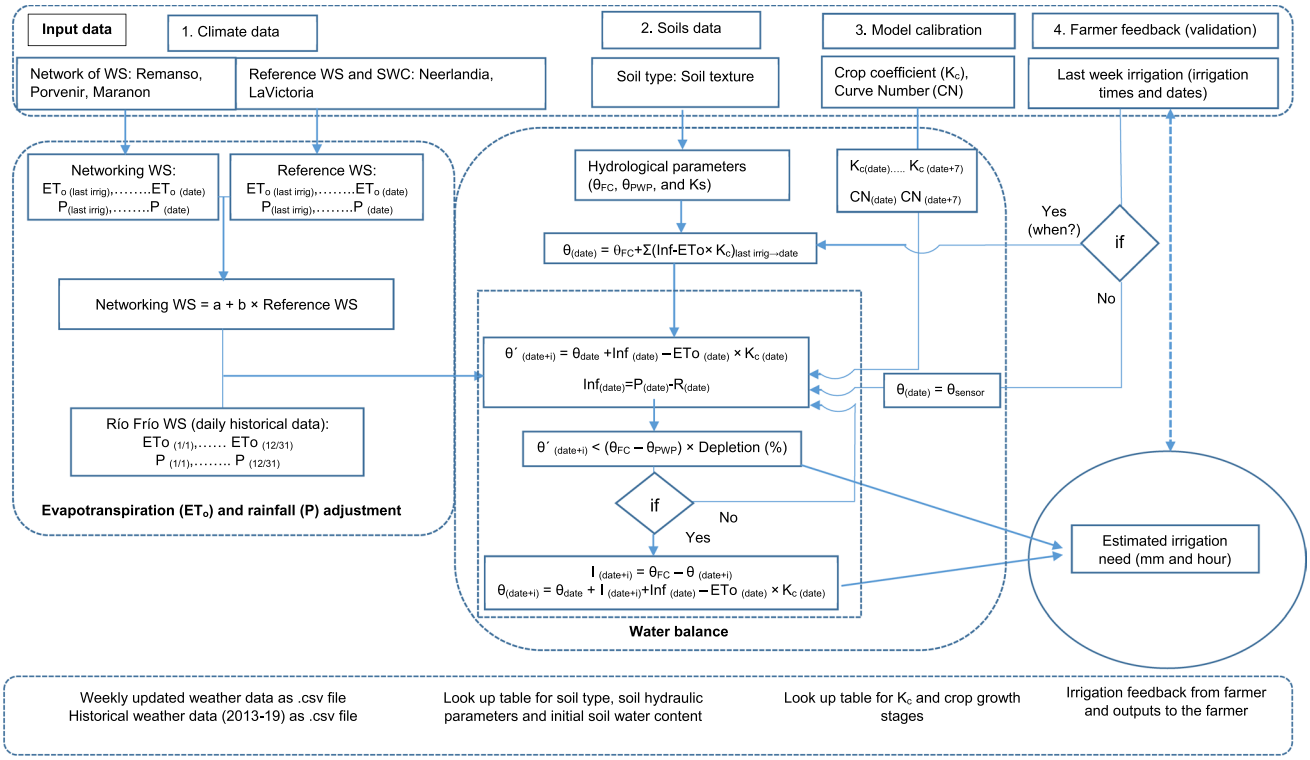
$$\Delta\theta = \theta_t - \theta_{t-1} = I_t + \mathrm{Inf}_{t-1} - \mathrm{ET}a_{t-1} - D_{t-1}, \quad (1)$$

$$P_{t-1} = R_{t-1} + \mathrm{Inf}_{t-1}, \quad (2)$$

$$\mathrm{ET}a = \mathrm{ET}o \cdot kc, \quad (3)$$

where θ represents soil water content, t time, I irrigation, Inf infiltration, $\mathrm{ET_a}$ actual evapotranspiration, $\mathrm{ET_o}$ reference evapotranspiration, k_c crop coefficient, D deep percolation, P precipitation and R runoff.

To deliver weekly recommendations, since we could not measure daily θ on each smallholder farm, we set θ to θ_{fc} on the date when each farmer reported the last irrigation event and then estimated θ_t (assumes t represents the day when the recommendation is delivered) aided by Eqs. 1, 2 and 3. The estimated θ_t was then compared to the trigger irrigation level: if θ_t was lower than θ_{tr} (soil water content triggering irrigation threshold) then $I_t = \theta_{\mathrm{tar}} - \theta_{\mathrm{tr}}$ would be required (θ_{tar} target soil water content). If irrigation was required, then the resulting soil moisture was updated to make θ_t equal θ_{tar}. Otherwise, the initial estimated θ_t was used for forward weekly running of the model. The target soil water content was field capacity (θ_{FC}) with irrigation triggered at a given depletion rate (35%) of the easily available water as defined by the difference between field capacity and permanent



Notes: θ_{FC}; Soil water content at field capacity (%), θ_{PWP}; Soil water content at wilting point (%), Ks; Hydraulic conductivity (mm/day)

Fig. 2 Conceptual workflow for data collection, processing and modelling of soil and water fluxes for an irrigated banana crop. *ETo* refers to reference evapotranspiration, *P* precipitation, *Inf* infiltration, *R* runoff, *Ks* is the saturated hydraulic conductivity of the soil, soil moisture (FC and PWP subscripts stand for field capacity and permanent wilting point, respectively)

wilting point (θ_{PWP}). Genutchen (1980) and Mualem (1976) models were used for estimating these soil water content values. In addition, θ_t was set to θ_{res} (residual soil water content) if the estimated soil water content dropped below the soil residual level. Each farmer's saturation and residual levels were retrieved from Carsel and Parrish (1988) based on their reported soil categories. A daily time-step was used for running the irrigation scheduling model and providing irrigation guidelines so we were forced to neglect time-dependent infiltration models (e.g. Green-Ampt, Phillip, Kostiakov or Richards). We used the SCS Curve Number method for its simplicity, due to the reduced number of parameters involved, and because of its widespread use for estimating runoff in agricultural lands (Lal et al. 2017).

Model fitting

For running the model, daily *P*, θ and ET_o were retrieved for the period November 2019–January 2021 from the weather stations. Deep percolation was estimated as the excess of water after soil saturation was reached. The saturation, field capacity, residual and permanent wilting point values were estimated using Genutchen (1980) and Mualem (1976) models. The parameters for those models were taken from Carsel and Parrish (1988) based on the soil textural classes for each farm determined in laboratory experiments with the samples collected during the field visits (Table 1). Therefore, only k_c and the curve number (CN) were undefined in the water balance. Both variables are highly dependent on crop status.

Table 1 Soil parameters for Neerlandia and La Victoria reference sites

Site	α (cm^{-1})	n	K_s ($cm\ d^{-1}$)	θ_{sat} ($cm^3\ cm^{-3}$)	θ_{res} ($cm^3\ cm^{-3}$)	θ_{FC} ($cm^3\ cm^{-3}$)	θ_{WP} ($cm^3\ cm^{-3}$)	Roots depth (m)
Neerlandia	0.01	1.23	1.68	0.43	0.089	0.33	0.19	0.6
La Victoria	0.036	1.56	24.96	0.43	0.078	0.16	0.088	0.6

Based on field visits, it was apparent that the phenological stage of banana crop development varied significantly between fields and individual estates. It was, therefore, not possible to define a fixed planting date and crop cover calendar to assign crop coefficients (k_c) across the region. Similarly, using a constant CN value was not appropriate for modelling as banana crop cover within plantations varies because of the asynchronous nature of crop development. The Neerlandia and La Victoria sites were used for calibration as the irrigation amounts at both sites was reported by the farm managers. We, therefore, derived values for k_c and CN by minimising the squared difference between θ estimates (using Eqs. 1, 2 and 3) and from field measurements. The k_c and CN values were estimated on a daily time-step to deduce equivalent average monthly values. Once the parameters were obtained the model was evaluated using a sample of six representative smallholder farmers. Model outputs included weekly irrigation scheduling advice (recommended timing and amount of irrigation) with information sent to the farmers via a SMS network. Weekly feedback from each farmer was then used to compare the modelled irrigation guidance against actual irrigation applications.

Results

Field survey analysis

The field survey was targeted to farmers of the reference sites and others in the region to collect relevant information on farming practices, soil types, irrigation systems and crop management practices. The soil characteristics for the two reference sites are summarised in Table 1 (θ_{sat} refers to soil moisture at saturation, n and α are the Van-Genutchen and Mualem model's parameters), soils in Neerlandia were silty clay loam, while loamy soils were present in La Victoria. Nearly a fifth (17%) of respondents reported course textured loamy soils. Most farmers (89%) reported using overhead irrigation (sprinklers) with the remaining farmers using gravity-fed surface irrigation. The majority (64%) of farmers in the region reported irrigating for 1–2 h per day.

In the Magdalena region, banana cultivars generally grown by farmers are *cvs*. "Gran Enano", "Valery" and "Williams" of the AAA Cavendish sub-group. The recommended average planting density was: *cv.* "Williams"—1475 ha^{-1}; however, it varies for *cv.* "Valery"—1650 to 1850 ha^{-1}; *cv.* "Gran Enano"—1850 to 2000 ha^{-1}. A recommended fertiliser dose of ground organic matter (1 kg plant^{-1}), phosphorus fertiliser (DAP 18-46-0, 50 g plant^{-1}) and fertiliser with boron and zinc (BOROZINCO 240 GR®, 16 g plant^{-1}) were applied before planting. Typically, the farmers fertilise 3–4 times every three months with DAP and urea. The typical planting period for banana varied between January and May. The length of growing cycle (planting to harvest) varies from 40 to 52 weeks; however, the average duration in the region was 49 weeks for the Cavendish sub-group. The crop attains approximately 90% crop cover and a maximum rooting depth of 0.6 m 37 weeks after planting. The selection of suckers for the following crop cycle is chosen 12 weeks after planting. There are typically 9–10 growing cycles (ratoons) following seed planting. The typical bunch weights, depending on whether it is the original seed crop or from suckers, is between 18 and 32 kg per bunch. Yields typically range between 20 and 22 tonnes ha^{-1} year^{-1} based on climate variability and location in the region.

Model fitting

Daily ET_o, P and θ for the period 14/11/19 to 01/01/21 was gathered from the Neerlandia and La Victoria reference sites and used for model fitting. After trialling different approaches (using different infiltration models for precipitation, temporal periods and minimisation functions), we achieved the best results using a multi-objective minimisation approach by minimising the squared difference between the estimated daily soil water content and the corresponding measured value. From these we obtained daily estimates of the CN and k_c to calculate monthly average figures to be used for deriving the weekly irrigation scheduling recommendations.

The model was forced to allow k_c and CN to vary between 0 and 2 and 50 and 99, respectively, to ensure the minimisation routines converged to a solution. Although the daily estimates showed high variability, the monthly average values were within a reasonable range as shown in Table 2 (FAO crop coefficients for banana in tropical areas range

Table 2 Summary standard deviation (SD) statistics for the calibrated values of average crop coefficient (K_c) and curve number (CN) for each month at each reference site

Month	Neerlandia		La Victoria	
	K_c (SD)	CN (SD)	K_c (SD)	CN (SD)
January	0.87 (0.71)	0.00	0.73 (0.53)	0.00
February	1.08 (0.64)	0.00	0.79 (0.46)	0.00
March	1.04 (0.57)	0.00	0.60 (0.44)	0.00
April	0.89 (0.68)	0.00	0.54 (0.63)	0.00
May	0.81 (0.72)	92.04 (36.44)	0.84 (0.62)	92.68 (42.17)
June	1.20 (0.67)	95.21 (32.38)	1.01 (0.69)	93.94 (35.02)
July	1.06 (0.67)	94.73 (31.77)	1.02 (0.70)	95.05 (43.16)
August	1.04 (0.74)	95.04 (43.31)	0.82 (0.67)	93.73 (45.68)
September	1.07 (0.64)	94.57 (41.86)	1.10 (0.79)	96.01 (48.03)
October	0.98 (0.65)	92.58 (41.26)	1.05 (0.65)	94.83 (44.48)
November	1.16 (0.62)	95.74 (35.97)	1.17 (0.72)	95.63 (38.21)
December	0.99 (0.6)	0.00	1.14 (0.69)	0.00

between 0.4 and 1.1). Model calibration resulted in accurate estimates of θ for both the Neerlandia and La Victoria reference sites as shown in Table 2 and Fig. 3. The absolute θ differences were within a reasonable range, particularly for the Neerlandia site. There were some marked differences for the La Victoria site probably due to external factors linked to days when no rainfall was reported resulting in much higher observed irrigation applications.

Assessment of farmer irrigation practices

Current banana smallholder farming water management practices are strongly influenced by the timing of the two drivers of irrigation demand, namely rainfall and evapotranspiration (ET). By analysing the climate data at the two reference sites (Neerlandia and La Victoria) the dry and wet periods during a typical season are clearly evident (Fig. 4). The data from the in situ soil moisture sensors at each site suggested that the farmers were over-irrigating,

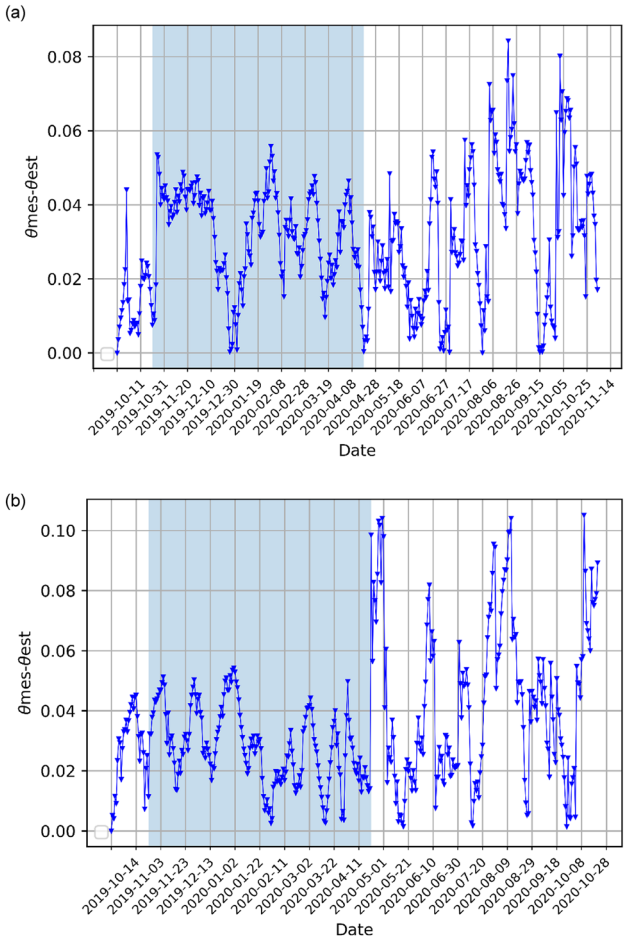


Fig. 3 Modelled absolute differences (cm^3 cm^{-3}) between estimated and measured θ for Neerlandia (**a**) and La Victoria (**b**) reference sites (shaded area corresponds to dry season)

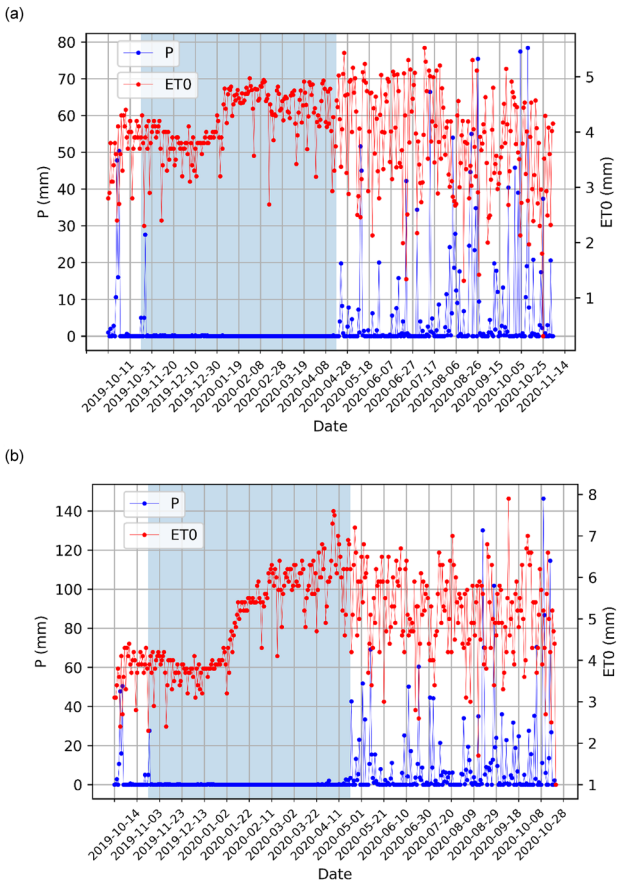


Fig. 4 Rainfall (P) and reference evapotranspiration (ETo) measured at Neerlandia (**a**) and La Victoria (**b**) reference sites. Shaded area corresponds to the dry season

with soil water content (θ) being kept close to saturation (Fig. 5) for most of the analysis period. Maintaining high soil water content (θ) levels in field is not recommended for agronomic, environmental or hydrological reasons. We therefore proposed to maintain the soil water content (θ) between field capacity and a depletion level of 35% (following FAO recommendations for banana) of the easily available water. Hence, when the θ dropped below the lower limit it triggered an irrigation to return the soil water content (θ) back to field capacity. With this criterion we simulated the expected changes in soil water content (θ) at both two reference sites (Fig. 6). Figure 7 presents both the estimated and the actual irrigation doses for the period analysed.

From Figs. 6 and 7, it is evident that although the farmers tend to over-irrigate throughout the dry season (θ) remains well above the irrigation trigger), θ tends to decline steadily throughout the second half of the dry period. This suggests that there was over-irrigation in the first part of the dry season when the soil was already above field capacity, but insufficient irrigation is then applied to replace ET in the second half of the dry season. Irrigation should therefore be reduced

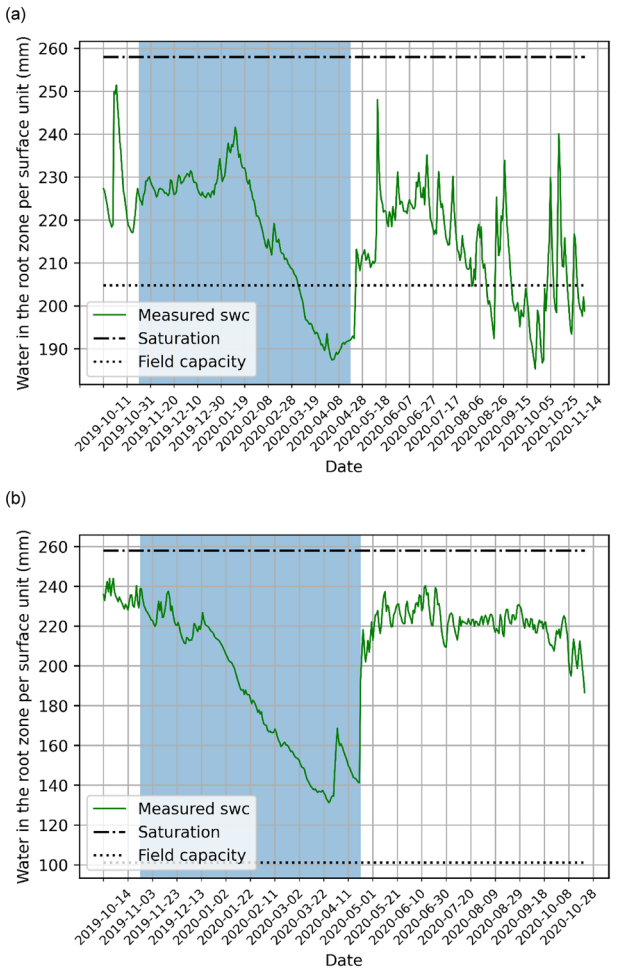


Fig. 5 Measured volume of water in root zone per unit of soil compared to saturation and field capacity at Neerlandia (**a**) and La Victoria (**b**). Shaded area corresponds to dry season

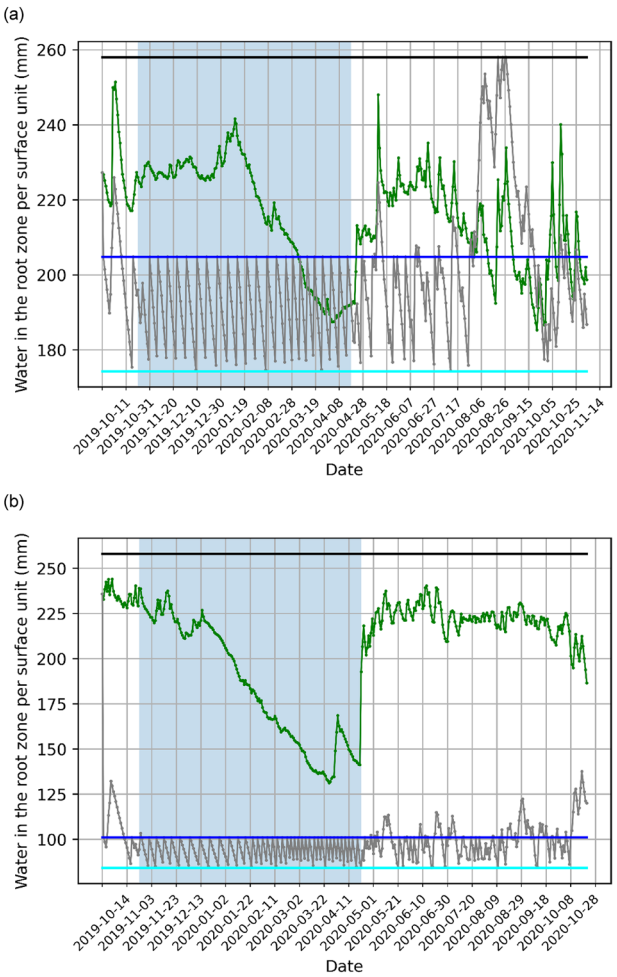


Fig. 6 Modelled changes in the volume of water in the root zone per unit of soil surface for the proposed irrigation schedule (estimate) compared with observed soil water content (θ) (measured) at Neerlandia (**a**) and La Victoria (**b**) reference sites. Shaded area corresponds to the dry season

in the rainy season to avoid saturation, and delayed until the irrigation threshold is reached early in the dry season, but then increased later to meet ET later in the dry season. Farmers tended to bring forward the start date for irrigation and then delay the end date, and frequently irrigated on a daily basis (or every other day) whilst the model recommended less frequent but larger application depths. As Fig. 7 shows, the model recommended farmers should irrigate with larger doses over longer irrigation intervals, but over a shorter irrigation season seeking to bring the soil water content back to field capacity. In reality, they were applying small and frequent applications over a much longer period. The model predicted a seasonal irrigation need of 1236 mm compared to 1063 mm as reported by the farmers (Fig. 8. However, further data on the amounts of irrigation actually applied by farmers is needed to improve model validation.

In addition to comparing irrigation practices at the two reference site farms, we also evaluated the utility of the model with a sample of six smallholder farmers by providing weekly irrigation scheduling advice via SMS and then collecting feedback on their actual irrigation practices. Irrigation scheduling guidance was based on estimated irrigation run times (minutes) rather than application depths (mm) in response to farmer requests. This may influence the accuracy of the scheduling advice given the numerous factors that can impact on irrigation run times including the application uniformity of the systems used and soil infiltration rates. Figure 9 summarises the farmers actual irrigation practices compared to the modelled recommendations.

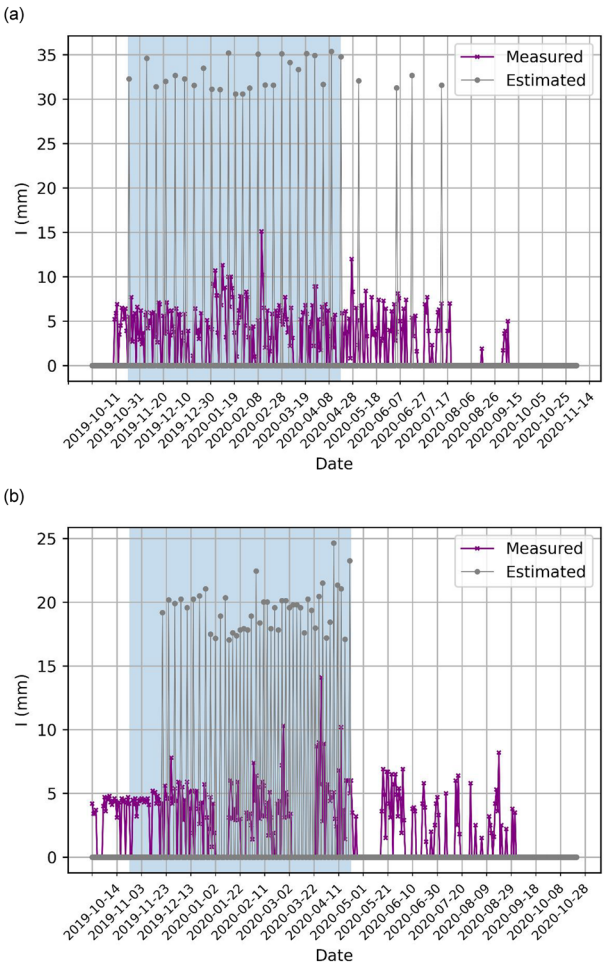


Fig. 7 Comparison of modelled estimates of irrigation need (mm) against reported application depths at Neerlandia (a) and La Victoria (b). Shaded area corresponds to the dry season

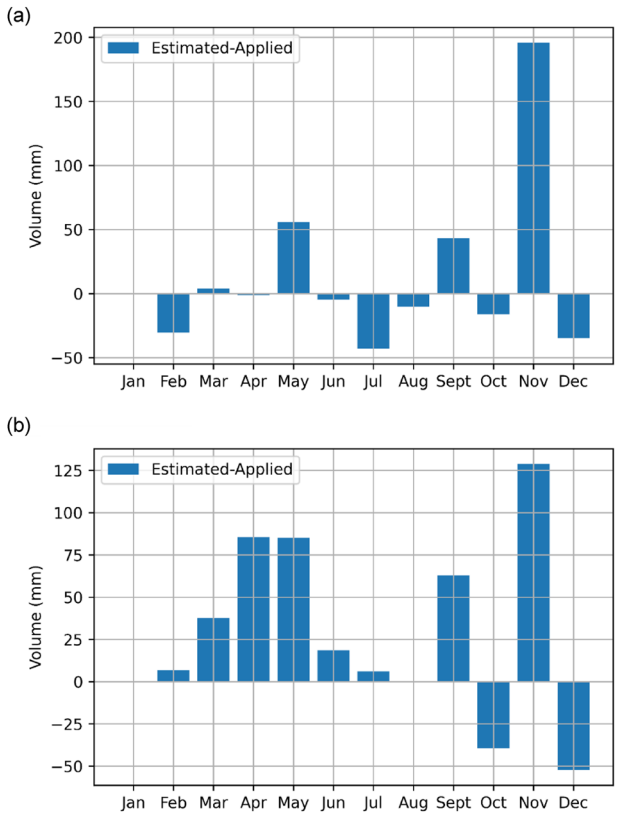


Fig. 8 Modelled monthly differences between simulated and reported irrigation needs (mm) at Neerlandia (**a**) and La Victoria (**b**) reference sites

Discussion

Modelling banana water requirements

The model adequately represented irrigation management practices at the two reference sites (Neerlandia and La Victoria) taking into account the spatial variability in soil types, agronomic and irrigation management practices. The modelling showed that both the reference sites and smallholders do not sufficiently adjust their irrigation schedules to differentiate between wet and dry seasons. This is likely to result in significant over-irrigation and increased water and nutrient leaching risks with consequences for crop yields. In this study, scheduling guidelines were developed based on a survey of 200 farmers in the region regarding the configuration of their irrigation systems. This data was then used to estimate typical discharge rates (mm h^{-1}), daily irrigation need (mm), volume (m^3) and time (minutes) for each scheduled irrigation event.

Key challenges for modelling banana water requirements

A paucity of relevant field data remains one of the major challenges to modelling soil water fluxes and estimating irrigation water requirements in banana plantations. A key challenge was in defining appropriate k_c values given the asynchronous nature of banana crop growth and development, both within fields and across individual farms. It was therefore difficult to define a typical cropping calendar and set suitable planting or sucker selection dates in order to define a crop coefficient curve. Although farmers tend to schedule sucker selection for harvest in January, in reality multiple crop phenologies exist within each farm. Farmers also select suckers from certain plants and replace older plants to maintain continuous production throughout the year. We, therefore, used the two reference sites for model calibration and to develop specific crop coefficients. The estimated values for La Victoria were lower than the k_c values measured by Bassoi et al. (2004) or Santosh and Tiwari (2019), while the values obtained for Neerlandia correlated better with those authors' findings. We also evaluated the feasibility

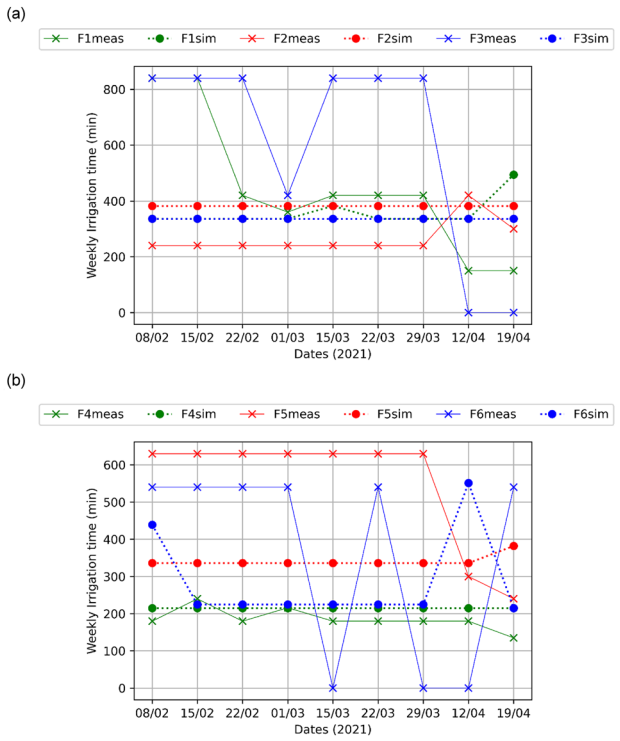


Fig. 9 Comparison of modelled weekly irrigation set times (minutes) against farmer reported actual irrigation timings. Data for farmers 1 to 3 (F1, F2, F3) shown in (**a**) and farmers 4 to 6 [F4, F5, F6 in (**b**)]. Act refers to actual; rec refers to model recommendation

of assuming a constant k_c value (1.1) as used by Santos et al. (2016) but this approach was not suitable. Similarly, there was a challenge regarding the choice of infiltration model, but the SCS Curve Number approach was selected for its simplicity. This was incorporated into the calibration to account for the wide range in precipitation rates observed in the area (up to 140 mm/day). As shown in Tables 2 and 3 robust results (CN average around 94) were obtained and consistent with values proposed for similar crops. Further work to incorporate experimental data to overcome the concerns raised by Turner (1995) in relation to rainfall interception is required since measured soil water contents represent the effective rainfall that has infiltrated through the canopy. The model also runs on a weekly time-step, so its accuracy will gradually improve over time due to reducing the effect from any biased data in the original calibration period.

Transferability of the modelling approach

The transferability of the modelling approach developed in this paper to other banana growing regions globally depends on many factors. First, the quality and availability of data is a key issue. In this study, data were collated and maintained through direct contact with those involved in commercial and smallholder farming who recognised the importance of data collection relating to soils, crop management and irrigation. In addition, the installation of automatic weather stations and in situ soil moisture sensors with global cloud networking functionality provided flexibility to gather information remotely. Secondly, the transferability of the assumptions made in this study is an important aspect. Most assumptions made were locality specific and would need to be modified for other geographies and contexts. This includes, for example, observed changes in crop and irrigation management practices, cultivar selection, the seasonal variability in crop growth due to variations in rainfall, ET_o and other agronomic and environmental factors. In these cases, it would be necessary to modify k_c values for different temporal scales to consider periods where banana growth does not align with typical patterns of crop development.

Methodological limitations

The development of a robust irrigation planning tool that includes soil water and irrigation fluxes for a tropical crop has many inherent challenges. These include the collection of locally relevant information on soils, agroclimate and cropping to support model calibration. Banana plantations are challenging environments for conducting experimental research due to extreme weather conditions and limited accessibility due to high planting densities, so equipment needs to be able to withstand high ranges in humidity and temperature as well as being robust to in-field agronomy practices. Conducting fieldwork in banana plantations is also challenged by the high canopy cover which often results in poor signals and network connectivity to mobile phone networks. In this study, 12 soil textural categories covering a number of observed soil physical properties were used. It was assumed that the reference sites and farmer fields had a defined single but uniform soil type (based on soil sampling), but spatial variability in soil texture exists across fields and impacts on the assumed physical characteristics modelled for the local soil. It is also important to consider uncertainties in field measurements, including errors

Table 3 Statistical summary metrics from model calibration

Reference site	RMSE ($cm^3\ cm^{-3}$)	Max. difference ($cm^3\ cm^{-3}$)	Average difference ($cm^3\ cm^{-3}$)	Max month difference
Neerlandia	0.0008	0.084	0.030	September
La Victoria	0.0045	0.105	0.035	October

associated with heavy rainfall events, unexpected ponding of water around the soil sensors, localised compaction, non-uniform rainfall distribution due to management practices (canopy pruning) and assumptions regarding crop cover and derived crop coefficient (k_c) values. Finally, translating model output such as irrigation depth (mm) to practical scheduling guidelines across a large region was a major challenge. Most farmers typically do not understand concepts of soil water or the impacts of ET_o variability on crop water use, and therefore prefer to irrigate based on time rather than depth, and therefore, it is important for recommendations to be converted from depth to time based on accurate information about local irrigation equipment and delivery rates.

Conclusions

The application of existing crop modelling approaches typically used for scheduling irrigation on field crops cannot be readily transferred to plantation crops such as banana because of the asynchronous nature of its crop growth and development. Different phenological stages and production cycles exist within a plantation. To support improved banana irrigation management, a tailored modelling approach was developed to account for the temporal variability in banana crop development whilst also addressing common issues relating to poor data availability on soils and crop management, a lack of knowledge on irrigation system and management and guidance on water demand for ratoon crops. Reasonably robust crop coefficient curves and curve number values were obtained based on a validated daily time-step simulation over a 1 year using field data from two reference sites. Although the farmers involved in the study found the irrigation recommendations useful, they were not generally adopting the weekly irrigation guidance recommended through the SMS service. Analysis of irrigation practices from farmer feedback showed only moderate to poor correlation between actual irrigation applications and the scheduling guidance. This implies a reluctance of farmers to change long-established traditional irrigation management practices, despite awareness of the impacts of over-irrigation on yield and nutrient leaching risks. Significant future research effort coupled with extension support will be needed to improve water management practices in banana plantation crops.

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Data availability The data will be available upon request.

Code availability The code will be available upon request.

Declarations

Conflict of interest The authors declare no conflict of interest/competing interest.

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