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IoT network to water management in an irrigation district: Study case in Colombia

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Abstract: One of the critical factors for crop efficiency is irrigation optimization. This optimization uses the knowledge of water dynamics in the soil to develop efficient irrigation programming. Previously, we described a prototype of a system that used soil moisture sensors to control the frequency and duration of the irrigation of a Limon Tahiti, showing a reduction in water and energy use. This paper describes IoT's use for optimizing irrigation for ten crops of socioeconomic importance in Colombia. Besides the soil moisture, the system also collects information on fruit growth and climatic variables. Results evidence a reduction in water consumption and several benefits for the crops, proving especially beneficial for small-scale agriculture.

Keywords: Field capacity, irrigation program, IoT, sensors technology, soil moisture, water management

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1. Introduction

Agriculture in developing countries faces many obstacles, such as interruptions in supply chains, labor shortages (Ministerio de Agricultura y Desarrollo Rural [MADR], 2020), the increase in the cost of agriculture supplies (FAO, 2021), and lack of knowledge and access to technology. These issues may lead to a global food crisis (von Grebmer et al., 2022). Against this background, Agriculture4.0 emerges as the integration of various technologies, such as the Internet of Things (IoT), to improve production processes and optimize resources (Soori, 2023). However, despite its importance, in many countries, the use of Agriculture 4.0 is incipient. For example, in countries like Colombia, only 5% of the productive units include some level of technology (IDEAM, 2019).

Efficient crop irrigation is critical, and IoT offers promising approaches for optimization (Vera et al., 2019; Gulati & Thakur, 2018). IoT-based systems use real-time soil moisture data to activate irrigation when levels fall below a specific threshold, resulting in time, money, and water savings. Previous work with a Limon Tahiti crop demonstrated a 42% reduction in water usage and 40% in energy consumption (Rios-Rojas et al., 2020).

This paper describes IoT's application (AgTech) for optimizing irrigation in ten crops of socioeconomic importance in Colombia, including avocado, cocoa, sugar cane, soursop, guava, Tahiti acid lime, corn, passion fruit, papaya, and vine. The system collects soil moisture, fruit growth, and climatic data, facilitating automated irrigation scheduling based on field capacity determination. Defining maximum and minimum field capacity thresholds and analyzing water storage dynamics in the root zone allowed identifying water excess and deficit issues.

The study successfully validated IoT's effectiveness for irrigation management across diverse crops, providing valuable experience for future projects.

2. Materials and methods

This paper is one of the results of the project "New Technologies to increase water use efficiency in Agriculture in LAC by 2030". This project was led by the Colombian Agricultural Research Corporation - Agrosavia, supported by the Association of Users of the irrigation district RUT - ASORUT, and financed by FONTAGRO.

The system was deployed in the department of Valle del Cauca, in the municipality of La Unión, in the RUT irrigation district (D.RUT). The district occupies 10,200 hectares and is located between the Western Cordillera and the Cauca River, in the north of the department, in the flat area of the municipalities of Roldanillo, La Unión, and Toro, Valle del Cauca, Colombia (Figure 1).

The RUT zone (RUT stands for Roldanillo – Unión -Toro, three municipalities in Valle - Colombia) is known as the fruit and vegetable pantry of Colombia, contributing to 50% of the food in Valle del Cauca, 12% of the fruit production national and 42% of the GDP of the department (ASORUT, 2018). One thousand three hundred fifty-three families live in the zone. These families depend exclusively on agricultural activity. The district area is 10,200ha, of which 77% correspond to cane and 19% to corn; fruit trees and scattered crops occupy the remaining area. Crops linked to the project represent more than 90% of the district area (ASORUT, 2018).

The Users' Association ASORUT (with 1,200 members) manages the district. The primary water source in the zone is the Cauca River. According to ASORUT (2018), the area has an average temperature of 24° C and an altitude of 930 meters above sea level. The rainfall cycle is bimodal, with an annual average of 1,015 mm; the annual evaporation is between 1,500 and 1,700 mm; the average relative moisture is 72%. However, in the project execution period, rainfall had an atypical differential behavior, with an excess of 75% for 2021 and 51% for 2022 (Figure 2).

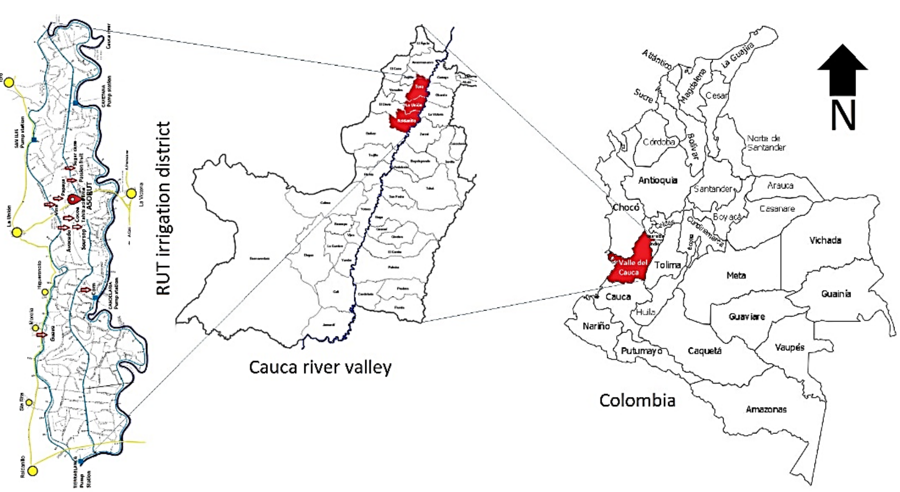


Figure 1. Location of the deployed system.

The soils of the district are very poorly drained, with a flat concave microrelief and clayey texture throughout the profile. The external drainage, in some cases, can be flooded for one or several months during the year; however, with the drains built, these lands have been able to be cultivated. They are deep soils with a slope that does not exceed 3% (IGAC-CVC, 2004).

Experiment setup. The IoT system consists of a wireless sensor network comprising by a) ten soil moisture measurement devices (one for each crop), these devices utilize locally manufactured electronics (datalogger) by Visualiti SAS, a regional Agtech startup. Each sensor node is equipped with an Atmel328 processor programmed to process and store data and transmitted remotely to the coordinator node using XBeeRadio and an omnidirectional 10dBi antenna. The soil moisture sensors employed are EC-5 by Meter; b) five repeater nodes; c) one coordinator node, also manufactured by Visualiti SAS working with an Atmega2560 processor programmed to receive and process remote data messages from nodes via DigiMesh. This network transmits information to the cloud via SIM900 GSM module on coordinator node covering a vast 10km area (Figure 3). This information is available to project scientists, the irrigation management system, and the farmers. Soil moisture measurement devices were installed at different root depths. In the case of avocado, it was installed at 30cm, cocoa at 25cm, cane at 20cm, guava at 30cm, soursop at 30cm, Tahiti acid lime at 30cm, corn at 15cm, passion fruit at 25cm, papaya at 20cm and vine at 20cm.

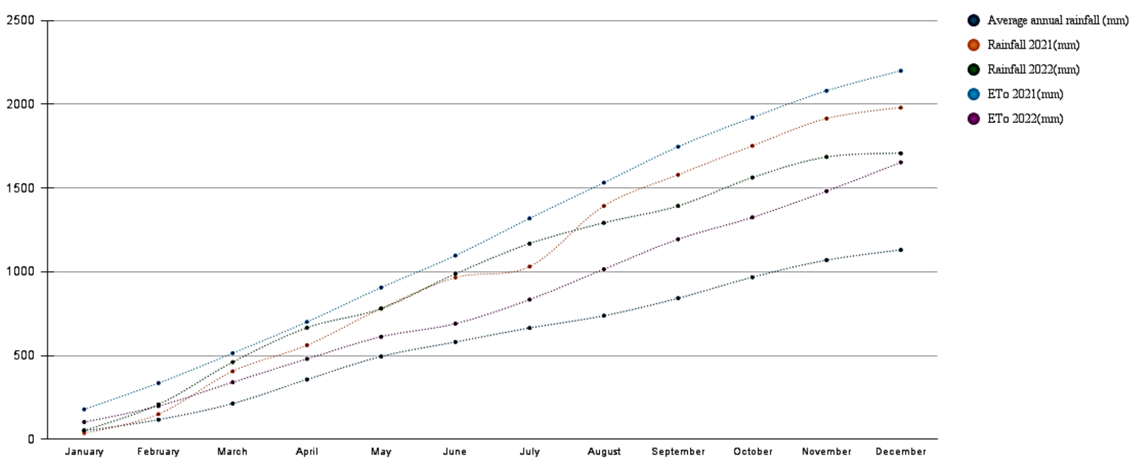


Figure 2. Accumulated rainfall and evapotranspiration.

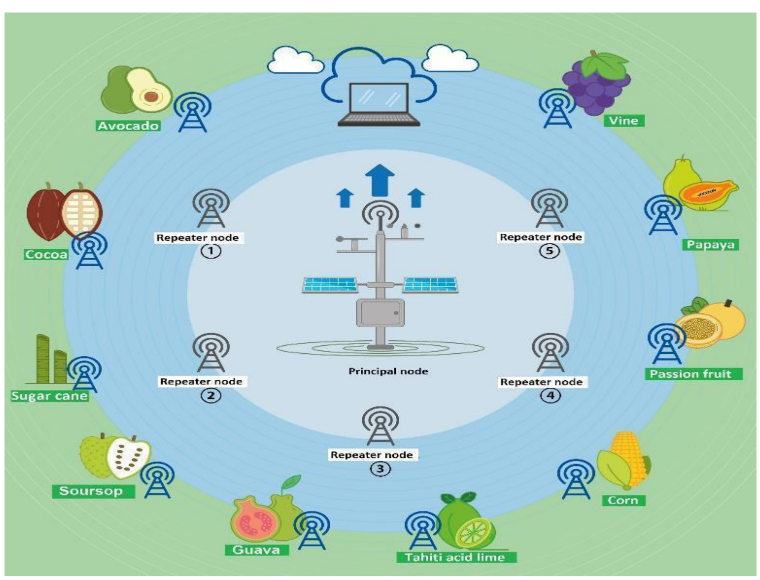


Figure 3. Architecture of the IoT system.

The information was collected from ten trees of each crop arranged as an orchard (avocado, cocoa, guava, soursop, Tahiti acid lime, and papaya) and ten furrows for the other crops (cane, corn, passion fruit, and vine). Two sensors were installed on each tree; that recorded the change in soil moisture every 20 minutes. Meteorological variables were also collected from three Davis Instruments weather stations equipped with a pluviometer, humidity and temperature sensor, anemometer, and a solar radiation sensor, operating independently of the soil wireless sensor network and sending data directly to the cloud, installed throughout the irrigation district. This information was collected for 22 months. In each crop, the diameter of the fruit was monitored with a high-precision digital caliper with an LCD screen for measurement visualization and manually recorded. Following an observational approach, the data was collected without further intervention or experimental tests.

Irrigation program. During the characterization of each site, farmers were inquired about the traditional method for determining the frequency and duration of the irrigation. The farmers based their decisions on the visual inspection of the soil moisture without any technical criteria. The average frequency of irrigation was three days. Based on the frequency and period values indicated by the producers (Table 1), an adjustment was made. The irrigation program was made directly from the soil moisture information. For the frequency, the time that elapses between the maximum permissible soil moisture for the crop, 0.8FC, and 0.8(0.8FC), equivalent to 0,64% FC, is quantified, at which time it must be irrigated again. In this case, for soils as clayey as those of the D.RUT, with slow internal drainage, priority was given to the oxygen content, preventing the soil from reaching 100%FC. This period was determined from the wetting process, that is, the time it takes for the irrigated soil to reach 0.8 FC.

Field capacity – FC. The data series collected from the capacitance sensors were also used to approximate the site's field capacity better. The results obtained by the laboratory for the moisture retention curve showed remarkably high values. Data series (comprised 72 data per day) showed repetitions of "drying events." This event presents a maximum, that is, a state of high moisture generated by irrigation or rainfall, which drains until a period of stable moisture and a minimum. This minimum also tends to be stable, and the soil loses moisture at an incredibly low rate. "Drying events" were analyzed independently for each crop. The "mode" was calculated during the stable section. This value was taken as the FC. Since even under stability, the moisture at FC can vary slightly; the FC was assumed as ±1% of this mode value. In addition to field capacity, from the soil moisture series, deficit, and excess moisture problems were identified, as well as their sources. Monitoring the crops allowed the effect of the moisture regime on the productive processes.

3. Results and discussion

Automated measurement and monitoring technologies from agriculture 4.0 are crucial in agricultural production (Santos Valle & Kienzle, 2020). In this study, we utilized soil moisture data to determine field capacity (FC) and proposed an irrigation program based on this information. Additionally, the soil moisture data helped identify drainage issues and their related water sources.

Field capacity – FC. Laboratory tests of soil samples showed high FC values. These values (41%) exceeded the FC of clayey soils (31 and 39%, according to Israelsen and Hansen (1985). Due to the above, it was decided to estimate the FC from the soil moisture data collected from sensors (Fazackerley & Lawrence, 2012; Sui, 2018; Vories & Sudduth, 2021). For the present study, this value was the mode of the data series. For this calculation, the temporality of the drainage was not considered, but rather the "stable" value of moisture at a given time (Shaxson & Barber, 2005). Some FC values were also above 41%. Still, it is considered a higher reliability of data since it is a value measured at the site (Sharma, 2019), for those periods after an irrigation or rainfall event; periods with enough repetitions to determine this data, since the soil moisture series corresponded to a period of 22 months, measured continuously with a frequency of 20 minutes. Table 1 shows the FC measured in the laboratory at a pressure of 0.33 Bars (Rai et al., 2017). Equally, it is shown the FC taken from the mode of the dataset. The latter values for FC were considered the most dependable as they were collected at the root site, without interfering with the soil, and in a free drainage condition. In addition, this value corresponds to the value reported in the literature for clayey soils, around 40% (Datta et al., 2017).

Table 1. Field capacity (FC) in experimental crops.

Crop	0,33Bars	Calculated from dataset
Avocado	42.7	38
Cocoa	47.6	34
Sugar cane	45.4	44
Soursop	41.4	40
Guava	44.8	36
Tahiti acid lime	55.2	36
Corn	52.5	46
Passion fruit	53.2	50
Papaya	42.2	36
Vine	42.7	48

Field capacity determined the irrigation program, setting irrigation frequency and period based on water depletion (Muangprathub et al., 2019). Maintaining soil moisture at 80%FC was considered optimal for crop gas exchange (Liyanage et al., 2022), while values close to FC increased CO2 production (Yiqi & Zhou, 2006). Irrigation frequency was guided by 80% of 0.8FC as permissible depletion, supported by studies from Yiqi and Zhou (2006) and Zhao et al. (2020). Table 2 presents a fixed irrigation program with basic parameters, while real-time IoT monitoring allows customized irrigation based on soil moisture dropping to 64%FC and stopping at 80%FC (Yiqi & Zhou, 2006). A continuous monitoring approach considers meteoric, underground, and consumption plant-atmosphere contributions. The fixed program suits producers without an IoT network but may lack precision compared to farm-specific data. Implementing the irrigation program (0.8FC and 0.64FC) increased frequency, saving over 50% of water use on average (compared to the previous 3-day frequency).

Deficit and excess of soil moisture. This section describes some of the most important problems associated with deficit and excess moisture. Before analyzing the effects of excess and deficit conditions, the causes for these scenarios will be presented. In addition to the excesses of rainfall shown in the 2021-2022 period (already illustrated in Figure 2), there are moisture accesses from the irrigation and drainage channels of the district. As can be seen in Figure 4, some of the experimental crops are located a short distance from the main channels of the D.RUT. Avocado, cocoa, soursop, guava, Tahiti acid lime, and vine crops are close to and influenced by the interceptor channel, on the west side of the D.RUT. Cane and passion fruit crops are close to the main drainage channel. The direct influence of channels is not observed for maize and papaya crops.

The clearest case influenced by the channels is presented with avocado (Lorena variety), which is influenced by an irrigation channel that surrounds the crop (Figure 5). The water to orchard access subsurface and the soil moisture maintained above FC (Figure 6).

The evaluation was made for four complete productive cycles in avocado crops showing an average development period of 155 days, with an average diameter of 9.07 cm, at harvest (Figure 6). This size is greater than that reported by López-Galé et al., 2022), for landraces (8.9cm). This result indicates that these fruits have a longer permanence on the tree; considering that in tropical condition is reported 143 days for the Lorena avocado, with a diameter of 9.05cm, at physiological maturity. All these results indicate that monitoring of soil moisture can contribute to drainage management, preventing the negative effect of excess moisture (Chaikiattiyos et al.,1994).

Table 2. Irrigation program.

Species	FC	m*	0,8CC Maximum limit	0,8(0,8CC) Minimum limit	Frequency (days)	Irrigation time
Avocado	38	0.864	30.4	24.32	7	1,5horas
Cocoa	34	0.7992	27.2	21.76	7	40 min
Sugar cane	44	0.4968	35.2	28.16	14	1hora
Soursop	40	0.8712	32	25.6	7	1hora
Guava	36	2	28.8	23.04	3	40 min
Tahiti acid lime	36	0.7488	28.8	23.04	8	1hora
Corn	50	0.8136	40	32	10	40 min
Passion fruit	28	0.6552	22.4	17.92	7	20min
Papaya	36	1.5408	27.2	21.76	8	40 min
Vine	42	1.5768	33.6	26.88	10	1hora

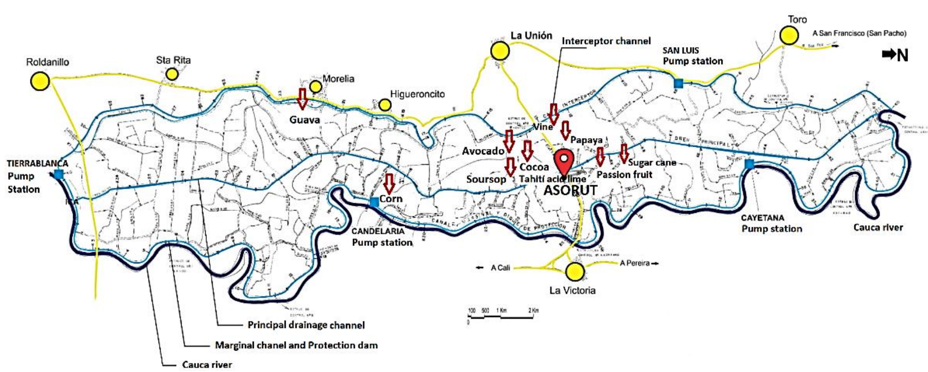


Figure 4. Crops' location (Font: ASORUT, 2018).

Figure 5. Irrigation channel in avocado crop.

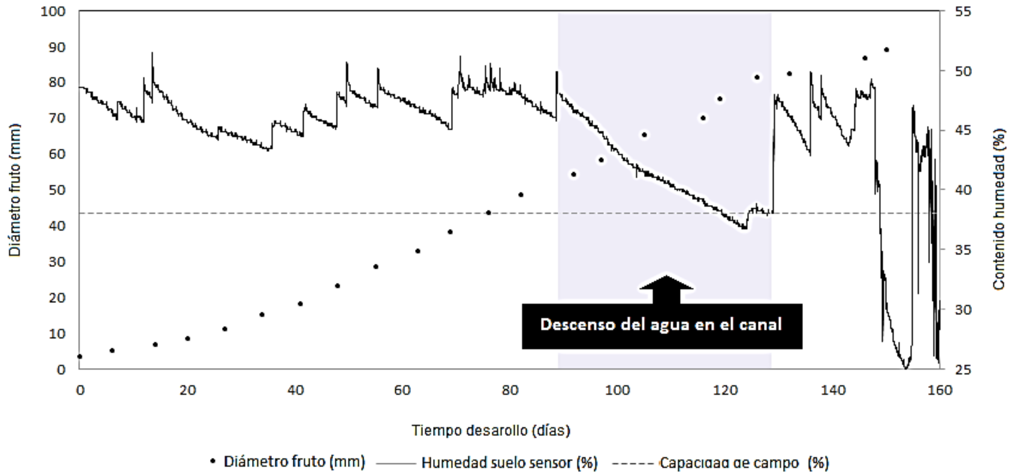


Figure 6. Growth avocado fruit curve vs soil moisture (θ).

In high water conditions, flowering is affected, as well as the production. This effect was observed in the flowering of September 2021. For December 2021, went water decline in the canal (lilac band, already illustrated in Figure 6), the crop flourished (Figure 7).

The study identified different water sources influencing the crop, enabling irrigation control and autonomous water management through a drainage system at a greater depth than the roots, benefiting avocado cultivation. A significant water use adjustment reduced consumption by 91%, facilitated by rainfall (Figure 6) and resulting in reduced fuel consumption and GHG emissions (Adhikari et al., 2019). Similar conditions were observed in cocoa (Figure 8), soursop (Figure 9), and guava orchards, located near the interceptor channel, with slow growth periods and late harvests. Figure 9 illustrates the decrease in canal water (lilac band) and rapid growth in soursop fruit.

Papaya also was developed in excess water conditions (excessive irrigation). In the north of Valle del Cauca, the crop was installed on raised beds of approximately 0.5m (Figure 10). This is done to isolate the roots from the high moisture soil.

Excess moisture enhances the infection of the crop with the Papaya ringspot virus - PRSV (Pokhrel, 2021). This virus causes premature wilting of the leaves. Thus, to meet the high-water needs (Auxcilia et al., 2020) and keep the soil close to field capacity (Fallas-Corrales & Van der Zee, 2020), it must be irrigated regularly. This requirement is understood by the producers in the north of the Valley, however when it is not possible to measure the soil moisture, this watering is exceeded.

Irrigation without technical criteria, or soil moisture data, generates problems of waterlogging in clayey soils, a problem that the producer does not observe, causing sanitary problems. Figure 11 shows the series of soil moisture measured at 20 cm in the root zone of the papaya crop.

Figure 7. Excess moisture effects over bloom.

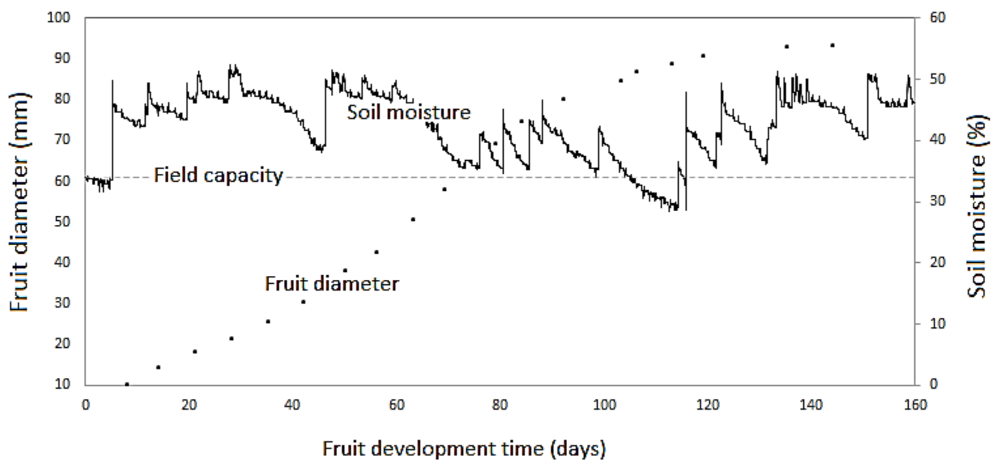


Figure 8. Growth cocoa fruit curve vs soil moisture (θ).

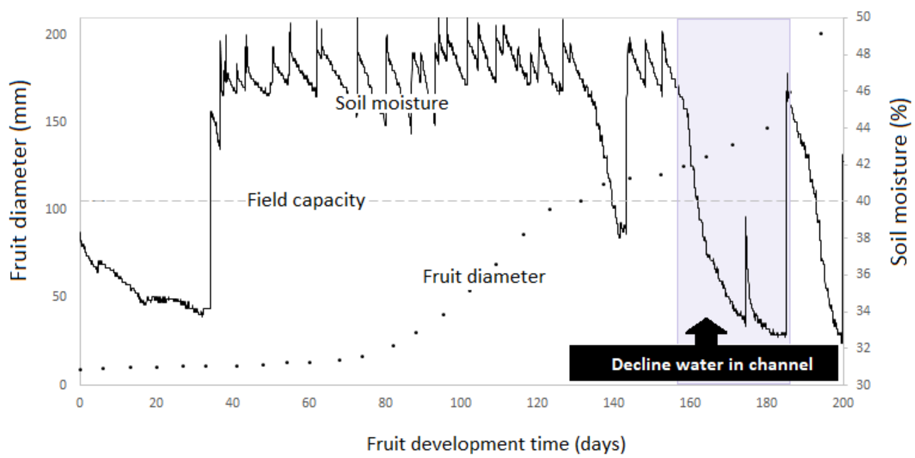


Figure 9. Growth soursop fruit curve vs soil moisture (θ).

Figure 10. Drainage system for papaya.

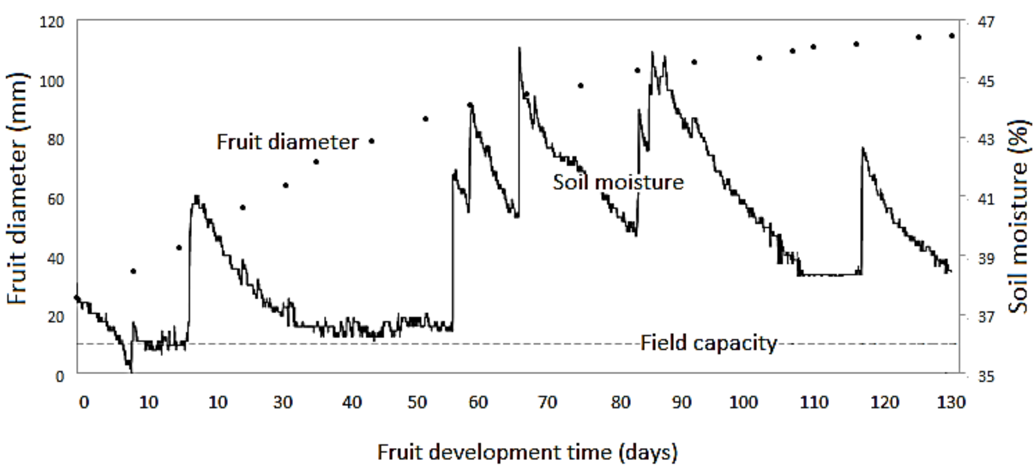


Figure 11. Growth papaya fruit curve vs soil moisture (θ).

Soil moisture exceeded field capacity during the production cycle, even with a drainage system in place. Daily papaya irrigation in the D.RUT, especially in the absence of rain, along with clayey texture and shallow root depth, minimizes bed effects. Measuring soil moisture allows regulating water use and maintaining plant health, protecting crops from papaya PRSV virus, historically affecting the north of Valle del Cauca, Colombia (Chaves-Bedoya & Ortiz-Rojas, 2015). Data analysis revealed that certain crops, like corn, passion fruit, Tahiti acid lime, and sugarcane, experience prolonged periods of soil moisture deficit. They rely on calendar and rainfall criteria, neglecting soil moisture storage. The shallowness of sugarcane and corn roots exposes them to drying, particularly the topsoil layer affected by radiation, leading to a dryer storage zone (Figure 12). Another concern is soil salinity, prevalent in the irrigation district RUT due to the Cauca River, a primary irrigation source and the main drainage of Cauca Valley (Echeverry-Sánchez et al., 2017).

In the case of passion fruit crops, the system made it possible to identify that the producer would have an error in his irrigation program that affects the harvest period. It was quantified that the crop remained around 65 days with a moisture under 0.64FC, in the fruit filling phase. The irrigation program has for producer priority root health, since this crop is sensitive to water stress for floods (Teixeira, 2023). For this reason, the producer irrigates lesser, moreover it is based on rainfall regime and the production system is in raised beds.

For Tahiti acid lime, the fruit developed in complete deficit. As can be seen in Figure 13, the moisture was kept under 0.8CC and in the filing period under 0.64CC.

The period measured for the development of the fruit of the Tahiti acid lime in the condition of the RUT irrigation district is 110 days to reach an equatorial diameter of 56mm. This diameter refers to the criteria used to define harvest maturity according to NTC 4087 (Instituto Colombiano de Normas Técnicas y Certificación [ICONTEC], 2021). This time exceeds those measured in research in the productive condition of Palmira, Valle del Cauca. In this case, times have been measured in Palmira-Agrosavia research center for the development of the fruit of 89 days for a diameter of 55mm. Even for both conditions, the caliber exceeds the minimum acceptability of the Tahiti acid lime in the market, 45mm (ICONTEC, 2021); which indicates that the fruit remains in the field for longer periods than necessary for harvest. Based on the monitoring results, the producer has been recommended to irrigate more frequently, going from a frequency of 8 to 5 days. Other studies have reported adjustments in irrigation frequency and volume for Tahiti acid lime using Agriculture 4.0 technologies. In this case, Rios-Rojas et al. (2020) reported a decrease in the use of water for irrigation of 42%, in the soil-climatic condition of Tolima, even increasing the frequency to two irrigation days, but decreasing the period. With this, it was also possible to improve the health condition of the orchard affected by a physiopathy, caused by prolonged water deficit (Rios-Rojas et al., 2020).

Adjustment of water supply. Based on the information collected by sensors during the productive cycles for each crop in the experimental period, the decrease in water consumption (m3*ha 1) was evaluated. Irrigation baseline was calculated from the data collected on the farm, Table 3 shows the number of irrigations and the volume used in each one.

In addition to regulating irrigation events based on data, drainage was conducted at the avocado cultivation site, which had reduced subsurface water access. Figure 14 shows the avocado crop between January-April 2023. Although excess water continues, it is only due to rainfall.

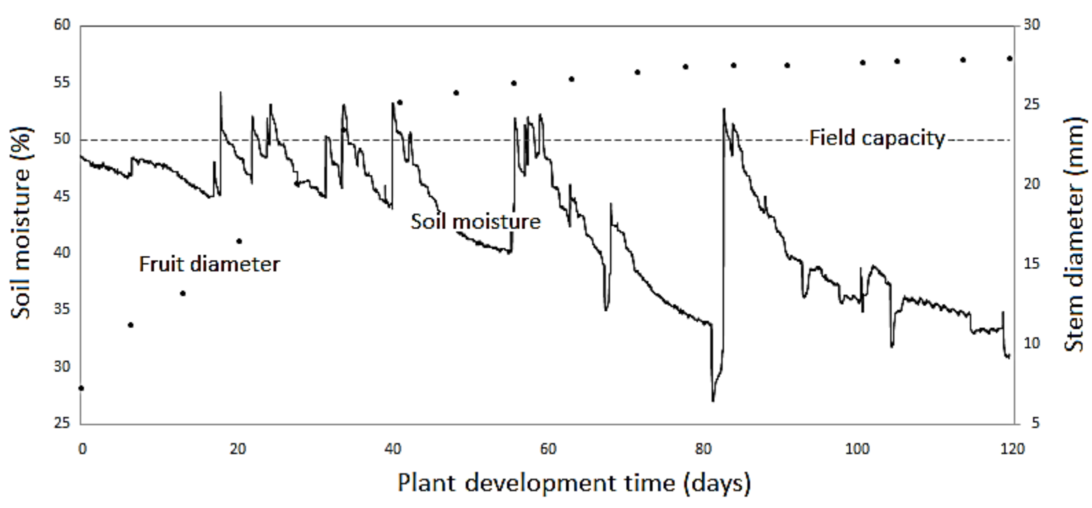


Figure 12. Growth corn stem curve vs soil moisture (θ).

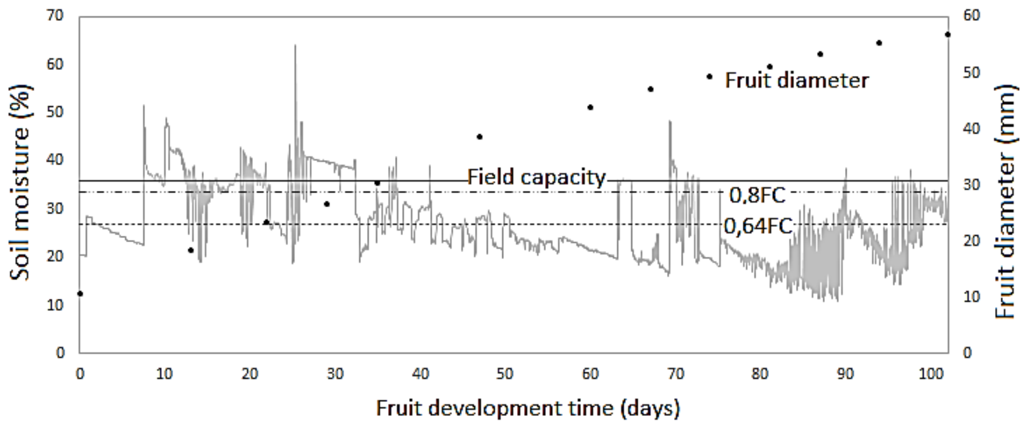
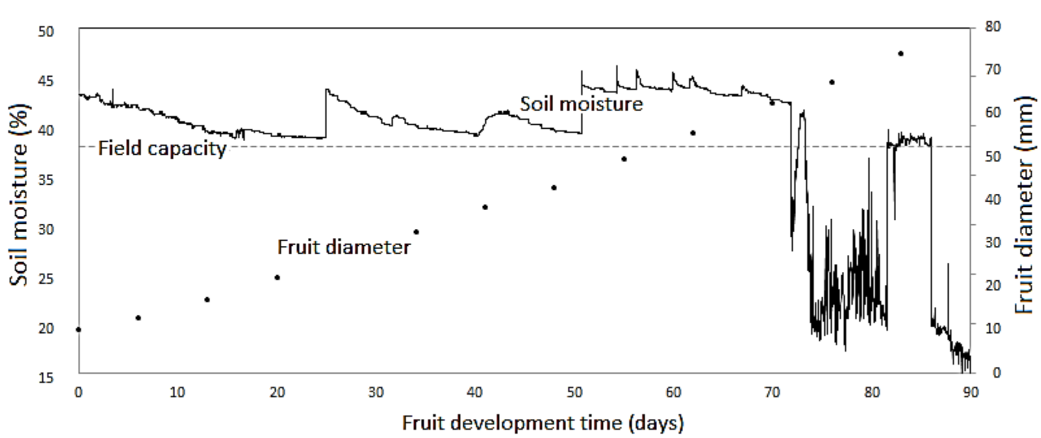


Figure 13. Growth Tahiti acid lime fruit curve vs soil moisture (θ).

Table 3. Producer water use vs experimental use.

Crops	Traditional irrigation		Adjusted irrigation		% Saving
	#irrigations *cycle-1	Total Volume (m3*ha-1)	#irrigations *cycle-1	Total Volume (m3*ha-1)	
Avocado	22	1,317	2	119	91
Cocoa	18	7,366	0	0	100
Sugar cane	23	156,867	4	0	100
Soursop	29	720	6	149	79
Guava	10	1,103	4	425	61
Tahiti acid lime	18	2,348	1	134	94
Corn	9	16,011	1	0	100
Passion fruit	73	9,788	0	0	100
Papaya	17	32,636	1	1,289	96
Vine	11	6,367	2	1,521	76

Figure 14. Growth avocado fruit curve vs soil moisture (θ).



4. Conclusions

Agriculture 4.0 has many technological options for crop management. These options not only improve productive conditions, but also provide management tools to improve the use of resources, making production more sustainable. Without excessive use of water and agrochemicals, the possibility of contaminating the soil and water sources decreases. The rational use of water and energy reduces economic investment, improving profitability.

Producers need to take advantage of the opportunity provided by technologies to share information and thus enhance associativity processes. According to the results of the present paper, farmers, especially those operating on a small and medium scale, could propose projects to government entities to cover larger areas.

As future work, it is envisaged the development of a Web application to generate early alerts that notify the moment (frequency) and period of irrigation directly associated with the data of the moisture sensor of the soil and/or the direct response of the plant, coupling a sensor to the network that measures a structure of the plant.

Conflict of interest

Some of the authors of this article (Bulla B, Gómez O, and Rodriguez R) are members of Visualiti SAS and have collaborated with the study. We acknowledge a potential conflict of interest as the company develops AgTech; however, we assure you that we have conducted the study with utmost objectivity, and the findings are based on an impartial evaluation supported by scientific evidence. The remaining authors have no conflicts of interest to declare.

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References

Adhikari, S., Mahapatra, P. S., Sapkota, V., & Puppala, S. P. (2019). Characterizing emissions from agricultural diesel pumps in the Terai region of Nepal. *Atmosphere*, *10*(2), 56. https://doi.org/10.3390/atmos10020056

Auxcilia, J., Manoranjitham, S. K., & Aneesa Rani, M. S. (2020). Hi-tech cultivation practices in papaya for augmenting productivity. *International Journal of Current Microbiology and Applied Sciences*, *9*(05), 636-645. https://doi.org/10.20546/ijcmas.2020.905.070

ASORUT (2018). *Características generales distrito de riego RUT*. Valle del Cauca, Colombia. Segunda edición. Available on: https://asorut.com/

Teixeira, E. C., Matsumoto, S. N., Pereira, L. F., Castellani, M. A., de Souza Almeida, C., dos Santos, C. E. M., & Lopes, J. C. (2023). Paclobutrazole use as a tool for anticipate water stress response of sour passion fruit. *Scientia Horticulturae*, *307*, 111480. https://doi.org/10.1016/j.scienta.2022.111480

Chaikiattiyos, S., Menzel, C. M., & Rasmussen, T. S. (1994). Flo ral induction in tropical fruit trees: effects of temperature and water supply. *Journal of Horticultural Science*, *69*(3), 397-415. https://doi.org/10.1080/14620316.1994.11516469

Chaves-Bedoya G. & Ortiz-Rojas L. 2015. *Genetic variability of Papaya ringspot virus isolates in Norte de Santander – Colombia*. Agronomía Colombiana 33(2), 184-193. https://doi.org/10.15446/agron.colomb.v33n2.50095

Datta, S., Taghvaeian, S., & Stivers, J. (2017). *Understanding soil water content and thresholds for irrigation management*. Division of Agricultural Sciences and Natural Resources, Oklahoma State University. Oklahoma Cooperative Extension Service. Recuperado de: https://shareok.org/bitstream/handle/11244/317091/oksa_BAE-1537_2017-06.pdf?sequence=7

Echeverr-Sánchez, A. F., Angulo Rojas, P. A., Saavedra Corredor, D. M., Pérez, C. F., & Urrutia Cobo, N. (2017). Evaluación del riesgo de salinización de los suelos del distrito de riego RUT Colombia. *Orinoquia*, *21*(1 Sup), 76-82. https://doi.org/10.22579/20112629.433

Fallas-Corrales, R., & van der Zee, S. E. (2020). Diagnosis and management of nutrient constraints in papaya. In *Fruit Crops* (pp. 607-628). Elsevier. https://doi.org/10.1016/B978-0-12-818732-6.00042-3

Fazackerley, S., & Lawrence, R. (2012). Automatic in situ determination of field capacity using soil moisture sensors. *Irrigation and drainage*, *61*(3), 416-424. https://doi.org/10.1002/ird.646

FAO. (2021). Colombia | Medios de vida agrícolas y seguridad alimentaria en el contexto de COVID-19: Informe de monitoreo – Mayo, 2021. Roma. https://doi.org/10.4060/cb4645es

Gulati, A., & Thakur, S. (2018). Smart irrigation using Internet of Things. 8th International Conference on Cloud Computing, *Data Science & Engineering (Confluence)*, 819-823. https://doi.org/10.1109/CONFLUENCE.2018.8442928

Instituto Colombiano de Normas Técnicas y Certificación [ICONTEC]. (2021). Frutas frescas. Lima ácida Tahití. Especificaciones. Icontec. Available on: https://ebooks.icontec.org/pdfreader/frutas-frescas-lima-cida-tahit-especificaciones

Instituto de Hidrología, Meteorología y Estudios Ambientales, [IDEAM]. (2019). Estudio Nacional del Agua 2018. Bogotá: IDEAM, 452 pp. Recuperado de: https://cta.org.co/descargables-biblionet/agua-y-medio-ambiente/Estudio-Nacional-del-Agua-2018.pdf?

Instituto Geográfico Agustín Codazzi (IGAC) y Corporación Autónoma Regional del Valle del Cauca (CVC). (2004). Levantamiento de suelos y zonificación de tierras del departamento de Valle del Cauca. Bogotá: El Instituto, 2004. Geoportal CVC. Recuperado de: https://geo.cvc.gov.co/arcgis/rest/services/SUELO/Suelos_Estudio_General/MapServer

Israelsen, O. & V. Hansen. (1985). Principios y aplicaciones del riego. Ed. Reverté. Barcelona.

Liyanage, D. K., Chathuranga, I., Mori, B. A., & Thilakarathna, M. S. (2022). A simple, semi-automated, gravimetric method to simulate drought stress on plants. *Agronomy*, *12*(2), 349. https://doi.org/10.3390/agronomy12020349

López-Galé, Y., Murcia-Riaño, N., Romero-Barrera, Y., & Martínez, M. F. (2022). Morphological characterization of seed-donor Creole avocado trees from three areas in Colombia. *Revista Chapingo. Serie horticultura*, *28*(2), 93-108. https://doi.org/10.5154/r.rchsh.2021.06.010

Ministerio de Agricultura y Desarrollo Rural – MADR. (2020). Adopción del Plan Nacional de Riego 2020-2039. Recuperado de:https://www.minagricultura.gov.co/Normatividad/Resoluciones/RESOLUCI%C3%93N%20NO.%20000311%20DE%202020.pdf

Muangprathub, J., Boonnam, N., Kajornkasirat, S., Lekbangpong, N., Wanichsombat, A., & Nillaor, P. (2019). IoT and agriculture data analysis for smart farm. *Computers and electronics in agriculture*, *156*, 467-474. https://doi.org/10.1016/j.compag.2018.12.011

Pokhrel, B. (2021). Effects of environmental factors on crop diseases. *Journal of Plant Pathology and Microbiology*, *12*, 553.

Rai, R. K., Singh, V. P., & Upadhyay, A. (2017). *Planning and Evaluation of Irrigation Projects. Methods and Implementation*. Chapter 17, Soil Analysis. https://doi.org/10.1016/B978-0-12-811748-4.00017-0

Rios-Rojas, L., Chaali, N., Jaramillo-Barrios, C. I., Ouazaa, S., & Correa, J. F. (2020). Irrigation and nutrition as criteria for adequate management of Tahiti acid lime trees affected by a physiological disorder in tropical conditions. *Scientia Horticulturae*, *270*, 109438. https://doi.org/10.1016/j.scienta.2020.109438

Santos Valle, S., & Kienzle, J. (2020). *Agriculture 4.0 – Agricultural robotics and automated equipment for sustainable crop production*. Integrated Crop Management. Vol. 24. Rome, FAO. Available on: https://www.fao.org/publications/card/fr/c/CB2186EN/

Sharma, V. (2019). Soil moisture sensors for irrigation scheduling. *University of Minnesota Extension. https://extension. umn. edu/irrigation/soil-moisturesensors-irrigation-scheduling*. https://extension.umn.edu/irrigation/soil-moisture-sensors-irrigation-scheduling

Shaxson, F., & Barber, R. (2005). Optimización de la humedad del suelo para la producción vegetal. El significado de la porosidad del suelo. Servicio de Manejo de las Tierras y de la Nutrición de Plantas. FAO, Roma. ISBN 92-5-304944-8. Available on:
https://www.fao.org/family-farming/detail/es/c/330047/

Soori, M., Arezoo, B., & Dastres, R. (2023). Internet of things for smart factories in industry 4.0, a review. *Internet of Things and Cyber-Physical Systems*.
https://doi.org/10.1016/j.iotcps.2023.04.006

Sui R. (2018). Irrigation Scheduling Using Soil Moisture Sensors. *Journal of Agricultural Science*, *10*(1). https://doi.org/10.5539/jas.v10n1p1

Vera, J., Conejero, W., Conesa, M., & Ruiz-Sánchez, C. (2019). Irrigation factor approach based on soil water content: A nectarine orchard case study. *Water*, 11, 1-15.
https://doi.org/10.3390/w11030589

Vories, E., & Sudduth, K. (2021). Determining sensor-based field capacity for irrigation scheduling. *Agricultural Water Management*, *250*, 106860.
https://doi.org/10.1016/j.agwat.2021.106860

von Grebmer, K., J. Bernstein, D. Resnick, M. Wiemers, L. Reiner, M. Bachmeier, A. Hanano, O. Towey, R. Ní Chéilleachair, C. Foley, S. Gitter, G. Larocque, & H. Fritschel. (2022). *Global Hunger Index: Hambre y Sistemas Alimentarios en Situaciones de Conflicto. Bonn: Welthungerhilfe; y Dublín: Concern Worldwide*. ISBN: 978-1-9161928-9-8. Recuperado de: https://www.globalhungerindex.org/pdf/es/2022.pdf

Yiqi, L., & Zhou, X. (2006). Soil Respiration and the Environment. Academic Press.*Processes of CO2 Production in Soil.* Elsevier.
https://doi.org/10.1016/B978-0-12-088782-8.X5000-1

Zhao, W., Liu, L., Shen, Q., Yang, J., Han, X., Tian, F., & Wu, J. (2020). Effects of water stress on photosynthesis, yield, and water use efficiency in winter wheat. *Water*, *12*(8), 2127.
https://doi.org/10.3390/w12082127