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Water Replenishment in Agricultural Soils: Dissemination of the IrrigaPot Technology

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Abstract

The challenge confronted by farmers during prolonged periods of soil water stress is to guarantee the restoration of water and maintain the productivity of agricultural crops. Even in regions such as Amazon, the variability in the precipitation regime should be considered in agricultural planning. There are regions in which 80% of annual rainfall is concentrated between December and June. It is exactly during this period of low rainfall that small-scale family-based farmers need technological assistance to guarantee that their crops remain irrigated in order to maintain their income in this rural environment. The IrrigaPot arises as an alternative that is able to access rainfall that has been stored since the rainy season and provide it to plants when the soil is dry. The pots are maintained full with 20 liters of water, and through capillary action the soil maintains them constantly humid. This technology does not require specific knowledge with respect to irrigation regimes and is necessary for the farmer to dedicate his time to replacing water. The technology is totally automated through a simple system using a float, tubes, and connectors that connect a rubber hose to the lids of the pots buried in the soil.

Keywords: sustainability indicators, water security, blue water footprint, agricultural productivity

1. Introduction

Small-scale family-based farmers oftentimes suffer considerable decreases in agricultural production during prolonged periods of soil water stress. Irrigation technology using clay pots buried in the soil is promoted as being an effective, accessible, and environmentally sustainable option for small-scale family-based farmers to be able to cultivate fruit trees and vegetables, and that can promote food security [1, 2]. Irrigation technology using clay pots buried in the soil has been used in important agricultural regions in the world [1, 3, 4] such as Burkina Faso, Zambia, the USA and Pakistan. Clay pots buried in the soil have been shown to be effective in the cultivation of fruit trees and in reforestation projects [1, 3]. This technique minimizes water losses due to evapotranspiration and soil drainage during irrigation in rural areas [5], improves seed germination and crop establishment [3], thus reducing crop loss and financial loss to farmers [1].

This technology aims to provide solutions that are able to supply a crop's water needs during long dry periods [6], especially in rural areas that require irrigation to guarantee agricultural production [7]. Adopting a holistic vision of water security in regions that have an increasing demand for water in order to produce food, this technology presents indicators that point to sustainability for food security as well as for the responsible use of water resources. Therefore, locally accessible innovations that improve the efficiency of irrigation systems are necessary in order to minimize undesirable losses due to evapotranspiration and soil drainage. Such practices aim to mitigate impacts on current analyses being conducted to study the climate as well as scenarios of global climate change. Quantification of evapotranspiration rates is fundamental to the evaluation of environmental sustainability indicators. In this context, the objective of this project is to strengthen research activities and share knowledge of technology that is low-cost and that has a small water footprint that uses rainfall water for hydrologic replenishment in soils agricultural systems.

There is a great need to increase research and extension actions that make viable the diffusion of the technology of the use of rainfall water to fill clay pots buried in the soil to maintain the production of agricultural crops during prolonged periods of soil water stress under actual climate conditions and those of future scenarios influenced by climate change, and to disseminate the results in order to amplify the adoption of this technology. In the course of using the technique, new strategies of low-cost irrigation can be adapted to different production systems and also in urban environments to increase sustainability in green spaces such as parks, public squares, schools and community gardens.

Managing irrigation water is among the critical issues to address food insecurity under the changing climate. Rainfall variability has been reported to significantly impact the economies of many countries as natural rainfall is the major source of water for agriculture. Clay pot technology has been proven to significantly improve crop water productivity in dry land areas but has not been promoted or used due to the lack of a suitable crop-specific standard design. In this context, the objective of this publication is to strengthen

research activities and share knowledge of technology that is low-cost, and that has a small water footprint that uses rainfall water for hydrologic replenishment in soils in agricultural systems.

2. Material and methods: low-cost and climate-smart irrigation technology

The experiment was carried out in northern Ethiopia and the results from this field work served as the data for several theses done at the University of Mekelle. The water seeps out through the micro-pores of the clay pots with relatively slow flow and larger surface wetting time, and thus promotes a greater area of coverage around the roots of plants. Contrarily, perforated clay pots leak water faster through the macro- and micro-pores and have relatively shorter wetting time and smaller area coverage.

On the other hand, the difference between perforated bars and round ones was simply the shapes of the pots which has to do with the area of coverage along the rows of the Swiss chard plant. Round types of pots were not as suitable as bar types (of the same volume) for rows of Swiss chard crops due to their wetting area coverage along the two sides of the bar.

Therefore, among the tested clay pot designs, the bar-shaped perforated clay pot designs were evaluated as best in terms of biomass yield and economic water-use efficiency. The water-use efficiency, economic aspects, and biomass for the perforated bar clay pot design were better than that of the bucket irrigation system. The other advantages of perforated bar clay pots over the bucket type is that the water source is inside the soil thus evaporation is almost zero and there is also less probability of occurrence of leaf disease due to wetting, and this ultimately improves the biomass and water-use efficiency.

2.1. Water-use evaluation

2.1.1. Measuring evapotranspiration using the surface renewal technique

$$LE = R_n - G - H \quad (1)$$

where, LE is latent heat flux, R_n is net radiation, G is soil heat flux, and H is sensible heat flux.

2.2. Calculation of surface renewal (SR) and measuring R_n and G

The calculation of SR is done using Eq. (1). This is a residual energy balance equation. The net radiometer and soil heat flux plate data will be measured every 5 minutes and then averaged and recorded at the end of each 30 minutes. Soil temperature data will be recorded at the end

of each 30 minutes, and the change in soil heat storage (dS) above the heat flux plates can be computed as in Eq. (2):

$$dS = VC \times ((T_{\text{final}} - T_{\text{initial}})/1800) \times D \quad (2)$$

where VC = apparent volumetric heat capacity of the soil; T_{final} and T_{initial} = final and initial temperatures for a 30 minute period, and $D = 0.04$ m = depth of the heat flux plate. The value 1800 is the number of seconds for each 30 minutes. The VC is calculated as the product of the apparent soil density and the specific heat. The soil heat flux density at 0.04 m depth (G_0) is calculated as the mean of the two heat flux plate measurements. Then the soil heat flux density at the surface (G) was calculated as:

$$G = dS + G_0 \quad (3)$$

2.3. Calculating surface renewal sensible heat flux

Temperature data was collected at a frequency of 4 Hz and the time lags of $r = 0.25$ and 0.5 s were used in a structure function to determine the temperature ramp amplitude (A_r) and inverse ramp frequency ($D + S$) as described [8]. The uncalibrated sensible heat flux density (H').

$$H' = q \times C_p \times ((A_r)/(D + S)) \times Z \quad (4)$$

where q is air density (kg m^{-3}); C_p = specific heat at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$) of the air; and Z is measurement height (m). A calibration factor (f) was used to account for uneven heating below the temperature measurement height and other potential issues [9] and to convert the uncalibrated H' to the actual sensible heat flux density.

$$H = f \times H' \quad (5)$$

The ' f ' values depend on the thermocouple size, sampling frequency, height above the ground, and the underlying vegetation [8–10]. A calibration factor was determined using a linear regression of sonic anemometer H readings versus H' data collected over a one-week period on the site.

Reference evapotranspiration (ET_0) was based on FAO-penman Montheith [11, 12]. Determination of crop coefficient (k_c) and actual and maximum evapotranspiration (ET_a and ET_c): from Eq. (1), LE can be related to ET_c or ET_a ;

$$k_c = ET_c/ET_0 \quad (6)$$

where ET_c is average crop maximum evapotranspiration per week; ET_o is the average weekly reference evapotranspiration.

$$K_s = ET_a/ET_c \quad (7)$$

where ET_a is actual evapotranspiration and k_s is the stress coefficient.

$$ET_a = k_s \times ET_c \text{ or } ET_o \times k_c \times k_s \quad (8)$$

2.4. Water-use evaluation in Africa

Water applied at each site was evaluated based on water held in the soil and data from production and harvest. Water-use efficiency is used as an important parameter to evaluate the performance of this technology. The water-use efficiency is calculated using harvest yield (kg) per m^3 of water applied to the crop. Water consumed (m^3) is obtained from the analysis of the hydrologic balance, and real evapotranspiration is calculated from measurements using the technique of surface renewal. Rainfall data were measured using a rain gauge installed at the site. Irrigation water was measured and applied using a gauged watering bucket. In the article "Evaluating water productivity of tomato, pepper and Swiss chard under clay pot and furrow irrigation technologies in semi-arid areas of northern Ethiopia" more detail about the agronomic data was presented [13]. A comparative study has been undertaken between bar shaped clay pot and furrow irrigation on tomato, pepper and Swiss chard plots in Mekelle University Campus, Tigray, Ethiopia. Plant height for both tomato and pepper was measured every week using a ruler starting from 30 days of transplanting until maturity. The number of fruits per plant and yield were measured during the cropping season, and the results showed that there were five successive harvests of tomato and Swiss chard whereas there were only two harvests from the pepper crop.

2.5. Economic evaluation: comparison based on a cost/benefit relation (CBR)

An analysis of cost/benefit relation (CBR) was done dividing the present value of the total benefit by the present value of the total cost for each farm; the larger the resulting index, the more efficient is the project. In general, a larger CBR indicates that the project is economically viable, and this also indicates that the technology used is economically efficient.

2.6. Statistical analysis of field data

Analysis of variance was conducted using a statistical program to evaluate the efficiency of water use, biomass production, crop yield, and plant height, width, and fruits, among other variables. Implementation of demonstration units of the Africa partnership was conducted with more than 60 farmers and 12 Agricultural Agents trained and provided with training manuals in the local language (**Figure 1**).



Figure 1. Images showing the demonstration of the project in Africa. Source: Araya and Africa team.

The interactive training and demonstrations delivered to university students, farmers and extension agents have contributed to enhancement of knowledge of using clay pot technology, which has contributed to enhance food productivity in dryland areas of Ethiopia. Cooperation in scientific knowledge sharing and development of partnerships with Brazilian Embrapa scientists has also been enhanced.

2.7. Amazon/Brazil: demonstration area

In Brazil, the process was fully automated and the experiments were installed in the community of Lavras, city of Santarém, in a fruit garden using agroforestry. This change in strategy led to substantial gains to the project. The project leadership in Brazil actively worked to automate the low-cost irrigation process. The entire pottery process was documented with video and photographs while the artisans from Icoaraci Center made the clay pots, and equipment for monitoring of parameters such as soil and air temperature and relative air humidity were purchased. The irrigation apparatus, comprising pipes, floats, connectors, hygrometers, gutters, and water tanks were purchased and the whole process in Brazil was automated. A Demonstration Unit (DU) was installed at Embrapa Eastern Amazon, in Belém. During the 39th Agriculture and Livestock Fair in Santarém, a lecture was given to demonstrate the low-cost technology for efficient water use (**Figure 2**).



Figure 2. Images showing the experiments installed in the Amazon sharing knowledge obtained from the Brazil partnership. Source: Martorano and Brazil team.

3. Results and discussion

The water seeps out through the micro pores of the clay pots with relatively slow flow and larger surface wetting time—area coverage around the roots of plants. Contrarily, perforated clay pots leak the water much quicker through the macro- and micro-pores and have relatively shorter wetting time—area coverage ratio. On the other hand, the difference between perforated bar and round types is simply the shape of the pots which affects the area coverage along the rows of the Swiss chard plant. Round types were not as suitable as the bar type (of the same capacity) for rows of Swiss chard crops due to their wetting area coverage along the two sides of the bar. Therefore, among the tested clay pot designs, the bar shaped perforated clay pot designs were evaluated as best in term of biomass and economic water use efficiency. The economic and biomass water use efficiency for the perforated bar clay pot design was higher than that of the bucket irrigation system. The other advantages with perforated bar clay pots over the bucket type is that the water source is inside the soil thus evaporation is almost nil and there is also less probability of occurrence of leaf disease due to watering and this ultimately improves the biomass and water use efficiency.

The highest economic performance was obtained in furrow irrigation during the first harvest due to higher investment in clay pots. However, after analyzing return on investment (six consecutive harvests) the bar shaped clay pot irrigation was highly superior in economic performance compared to the furrow irrigation practices. A marginal rate of return indicated that 478.18, 258.82 and 221.47% was obtained in Swiss chard, pepper and tomato, respectively. Sensitivity analysis also indicated that adoption of the findings is feasible and practical.

Comparisons of the irrigation methods using the clay pots showed that there was a significant difference ($p < 0.05$) for tomatoes irrigated in rows. The authors [13] infer that water availability was adequate and uniform in the clay pots compared to the irregular availability in the soil for the row-irrigated crops. The cumulative yield of the three vegetable crops irrigated using clay pots were significantly superior ($p < 0.05$) than crops irrigated in rows. There was a 30% increase in yield in the system where water was replaced using clay pots compared to the system wherein green pepper was irrigated in rows. These results show that the technology that irrigates using clay pots can be used even in conditions that use brackish or salty water. Furthermore, the yield of tomato was 32% greater using clay pots than for those irrigated in rows, thus confirming the efficiency of this system. Similarly, the yield of Swiss chard showed an increase in biomass of 51% using clay pots. This increase can be explained by the fact that Swiss chard has a shallow rooting system which facilitates the absorption of water in this system using clay pots as compared to irrigation in rows [4].

3.1. Expected results and importance of IrrigaPot technology: Amazon/Brazil

The expected results consist of the development of an irrigation technology using different intelligent solutions for the replenishment of soil water for different types of crops in Brazil (**Figure 3**), an increase in the number of farmers that understand the principles of this technology and that are able to develop new alternatives for the fabrication and use of these clay pots, development and testing of different forms of clay pots capable of satisfying crop water demand at low cost to producers, use of the successful results to create a specific line of credit for farmers to be able to fully use the IrrigaPot user-friendly, low-cost technology for water replenishment in agricultural systems, an increase in the supply and diversity of agricultural produce during dry periods, and an improvement in the quality of life of small-scale farmers thus allowing them to remain in the rural area using low-cost technology and reducing losses due to seasonal drought. Furthermore, we expect an increase in food security in a situation where rainfall variability threatens the food supply, and that rainfall storage will guarantee a water source with low or no loss of rainfall collected in the rainy season.

This technology will also provide greater opportunity and time for formal education due to the reduction in labor necessary to irrigate crops in the dry season, and thus help to eliminate child labor that is common in areas that have streams and small rivers used to supply water to crops, and will provide new opportunities to women that, now with more free time, can dedicate themselves to other artisanal activities or pursue a formal education, and production costs will therefore be reduced due to lower labor demand. Additionally, estimates of evapotranspiration will be used to help to plan a cropping strategy that uses water efficiently, with the water footprint as an indicator of crop sustainability for crops that adopt the IrrigaPot technology.

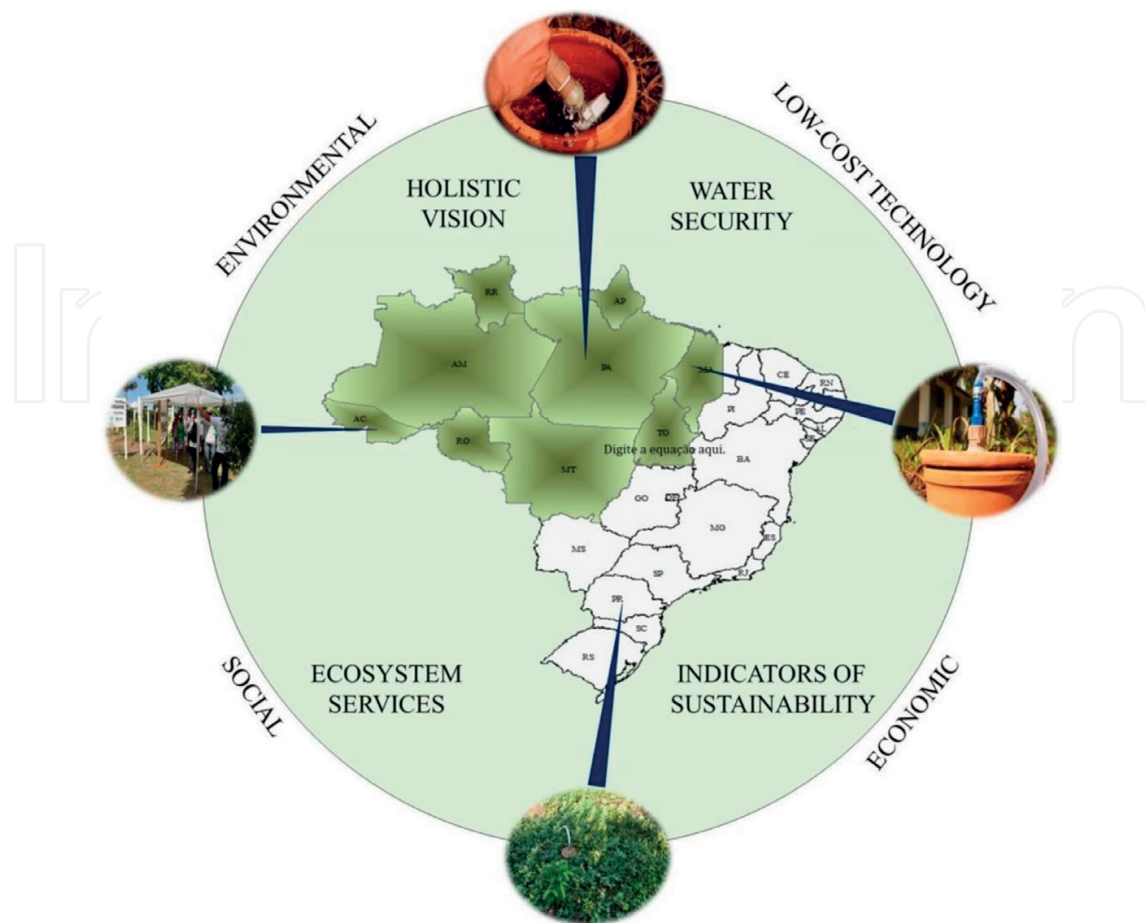


Figure 3. Monitoring and evaluation of water consumption, growth, development and productivity of crops (demands in northeast and southern Brazil).

The results from the Demonstration Units (DU) show gains in yield in the production of crops that use IrrigaPot technology by guaranteeing production during months with low rainfall. Agricultural producers express contentment due to the economic gains with the sale of products cultivated in areas using clay pots. In an interview [14] about the IrrigaPot Project, rural producers that cultivate using agroecological principles emphasized that the greater availability of water for plants guarantees gains and reduces preoccupation with crop failure, which allows them to engage in other activities on their property. The use of rainfall allows for the planting of species that previously could not be planted such as peanuts, tomatoes, peppers and achocha, associated with diverse fruit species. At the DU in the Lavras community (Santarém, Pará) plants maintained their production during the period of low rainfall in the region. Acerola plants and orange and tangerine trees guaranteed the availability of fruits at the local outdoor markets. Results published in different media sources [14–16] increased interest for the installation of this technology in new areas in many Brazilian States such as Acre, Tocantins, Amapá and Paraná (**Figure 3**).

The Brazilian Agricultural Research Corporation (Embrapa Amazônia Oriental/NAPT Médio Amazonas) presented this technology to organic producers, extension workers, and university professors and students highlighting the results from the Lavras community

(Santarém, Pará). The participants manifested interest in installing new units of the IrrigaPot project because they learned how rainfall could be used in agriculture during the dry months from August to November. The clay pots are maintained in the soil with 20 l of water and are able to meet plant water needs. It is important to emphasize that the use of rainfall waters reduced the blue water footprint of agriculture, because all the water used in irrigation comes from water that is stored during high-rainfall months in areas that adopt the IrrigaPot technology.

Using this process of collective learning, seminars were given wherein the fundamental techniques of irrigation with clay pots were presented in the DUs. Among the 150 participants in these activities, which were conducted in Altônia, in the northeast of the State of Paraná, the majority of them demonstrated interest in using this technology in their properties, but the largest barrier to this was established as the fabrication of the clay pots. This collective learning activity heightened the awareness of farmers of the importance of the adoption of this technology as a strategy for the sustainable cultivation of crops through replacement of water to soil during dry periods in order to guarantee production [17].

4. Conclusions

- The technology was found to be economically viable under conditions of small-scale growers, demonstrating the success of sharing scientific knowledge from the Brazil/Africa partnership.
- The sharing of knowledge about the IrrigaPot technology motivated agricultural producers from different regions of Brazil to adopt this technology as a strategy that promotes a pro-environment vision and that can bring social-cultural transformation with respect to the use of water resources in family-based agriculture.
- The partnership between the Brazilian Agricultural Research Corporation (Embrapa Amazônia Oriental), and the University of Makelle, da Ethiopia/Africa, with the incentive of the Program for Agricultural Innovation MarketPlace, integrated diverse specialists from Brazilian, African, Latin American, and Caribbean institutions in order to promote research projects and agricultural innovation and yielded successful results with the IrrigaPot project.
- This technology has gained the attention and interest of agricultural producers in different regions of Brazil and in neighboring countries, and also in Africa. These producers have installed the IrrigaPot system in different scales in diverse arrangements such as agroforests, and fruit and vegetable gardens, and have even adapted the system by modifying the type of clay pots.
- Society in general has increased pressure on governments and regulating agencies in order to provide incentive to agricultural producers to produce using with less irrigation water with the goal of reducing the environmental footprint of agriculture, principally the blue water footprint, and the IrrigaPot technology represents a sustainable practice for the sustainable replacement of soil water.

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