ECOLOGICAL RESTORATION AND FIELD IRRIGATION THROUGH CAPILLARITY

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Across the world different restoration projects for degraded ecosystems have resorted to irrigation in places with little precipitation, or to allow for planting/seeding outside of the rainy season, accelerate the establishment of seedling post-planting, or, more recently, to circumvent unexpected dry periods, originating from growing climatic instability. Here I describe an alternative irrigation system that I developed and have been improving, which seeks to facilitate forest restoration projects, but which also applies to forestry and to agriculture.

This alternative irrigation method is based on the physical principle of capillary action, or capillarity. This physical process occurs in very fine tubes, in which, without the use of energy, the molecules of a liquid adhere to the wall of the tube, allowing the liquid inside to rise vertically until it reaches an equilibrium with the force of gravity, at which point the elevation ceases (Figures 1a and b). Field irrigation through capillarity consists of using equipment that captures water in the deep soil layers and vertically conducing it, releasing it directly to the roots of a plant (Figures 1c and d).

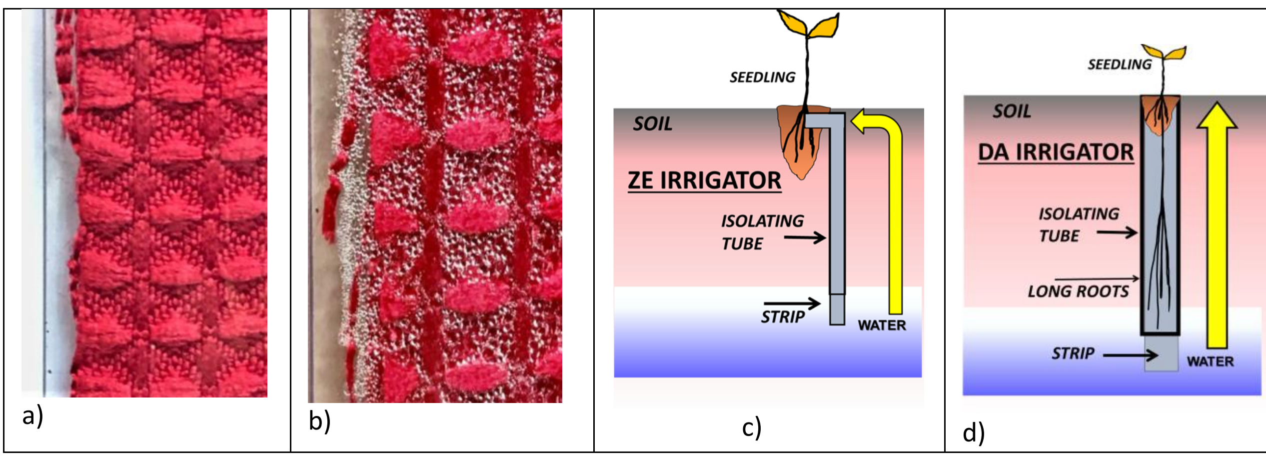

Figure 1: Field irrigation through capillarity. In a) detail of an irrigator made of a clear plastic tube and a fabric strip that will promote the elevation of water from the soil to the roots, and which in the image is not yet conducting water. In b) the same irrigator now showing the fabric already vertically transporting water through capillarity. It can be observed that water vapor has condensed on the fabric. In c) and d) diagrams showing the two types of irrigators that were invented and tested in the field to promote capillary irrigation. In c) a ZE irrigator (conductor material strip inside an isolating tube) placed in the soil and connected to the seedling clod; note that the water is elevated from the deep soil layers and penetrates the clod, moistening the roots. In d) a DA irrigator produced at nursery (seedling fixed to a strip of conductor material inside an isolating tube). In this type of irrigator, the seedling roots grow equally both on the surface of the strip at the clod, and along the strip as long roots descent along it until reaching the lower limit of the tube. To allow for the capture of water through capillarity, the end of the strips that is placed outside the tube should be in direct contact with a moist soil.

Since the Egyptians, irrigation follows, in general, two basic paradigms: withdrawal water from rivers, lakes, or, in current day, also ground water, which is used to moisten the soil, and provide water to the roots, in other words, irrigate the soil to irrigate the plant. The basic concept of this new technology subverts these two millennium-old irrigation paradigms.

Commonly in traditional irrigation water that is captured in one place is transported, stored and applied in another location, involving a large use of energy and large losses of part of the volume initially collected (through evaporation and/or percolation through deep soil layers).

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Aside from these losses, different traditional irrigation systems can produce direct damages (such as soil erosion or salinization) or indirect damages, resulting from withdrawal water from rivers, which reduces water availability for other uses of the river downstream, such as public water supply, electric energy generation, navigation, or fishing, in addition to reducing pollutant dilution, thus concentrating water pollution.
Worldwide, the withdrawal of water for irrigation represents more than 67% of the total withdrawal, while in Brazil this number is about 70%, leaving to society only about 30% of the existing volume, with major social and economic implications (Hofste et al., 2019).

In addition to these damages and problems, the use of irrigation implies a cost increase since, in most cases, water is brought from some place and distributed in the desired place, which demands an ongoing displacement of equipment and personal. Sometimes, there is no alternative, and without irrigation, the project cannot be developed, or the loss of plants makes the work infeasible. With irrigation being expensive, low income, rural property owners cannot use it, especially in semiarid regions, making restoration projects in these areas more difficult.

Field irrigation through capillarity is cheaper, because it does not use energy to work, does not require removing and transporting water from other locations, and does not even require large structures to deposit water in the desired location. By allowing the irrigators to be installed in the field and having continuous and autonomous functioning, the adoption of this alternative irrigation can facilitate forest restoration projects of different vegetation types, in different climates, soil types, or degradation conditions, increasing the chances of success for these projects. As the technology can be used to irrigate any kind of plant, it can be equally employed in forestry and in agriculture, eventually solving many of the problems caused by traditional irrigation in these production systems.

About field irrigation through capillarity

For the root of a plant to capture soil water through capillarity, there needs to be intimate contact between the soil particles and the roots. Breaking this contact by, for example, when the soil dries, interrupting the capture of water. Thus, also with field irrigation through capillarity, regardless of the material used to capture water, it is always necessary to guarantee that there is intimate and permanent contact between this material and the soil solution.

Capillarity irrigation does not use energy to work and, and once started, it continues indefinitely as long as there is water at the catchment point. However, for it to really occur there must be water in the soil, where the catchment point is.

The idea of creating irrigation equipment based on capillarity came from literature about the phenomenon of hydraulic redistribution in Amazonian tree species (Oliveira et al., 2005) and from the growing need to irrigate forest restoration plantings in São Paulo, due to the increase in rain uncertainty. Because of this, all of the equipment described here can generically be called Units of Water Redistribution (UWDs).

The use of capillarity as an irrigation method is old and has given rise to various equipment that move water over short distances for domestic use, in irrigation by wicks or in hydroponics. Different from what is proposed here, however, these irrigation systems capture water from reservoirs that need to be refilled with water coming from another location, while what we propose is capturing water on site from the soil.

Irrigation through capillarity done in the field can have other very important advantages, the main one being the absence of erosion, since water can be carried directly to the roots. With only a small volume of water being released at the roots, we can further reduce losses from evapotranspiration or by percolation to deeper soil layers. Another advantage would be the elimination of water losses from drift, common in sprinkling methods. Even if this irrigation were used only as a supplementary system, it would still be useful, since it could capture a portion of the water that seeps to deep soil layers and return it to the surface. In general, field irrigation through capillarity would avoid many of the direct and indirect damages caused by traditional irrigation systems.

The maximum height of a liquid reached through capillarity depends on various factors, among which are the nature of the liquid (here, water) and the quantity and width of spaces in the materials under consideration. Different materials, such as brick, wood, cellulose, paper and fabric, can capture and elevate a column of water to different heights. Thus, according to the interests or needs, it is possible to create different irrigating equipment using only one or various materials. The irrigators ZE and DA, tested using different conducting materials, worked satisfactorily, although each material tested carries its own different implications for use.

To irrigate a plant in the field through capillarity, it is necessary to capture water from deep layers of the soil profile, transfer it vertically and release it, ideally at the roots of the plants or in the surrounding soil. Therefore, to build functional irrigators it is necessary to find materials that can capture, transfer and release water.

After performing tests with many materials, I verified that the capacity to capture, transport and release water can vary greatly among them and even within one type of material. Indeed, absorption, conduction and release are distinct phenomenon, and while one material may be excellent at absorption, it may be practically incapable of conducting anything. Affecting this are factors such as the chemical nature of the material, the presence or absence of internal spaces capable or promoting capillarity, but also the abundance, dimension and connectivity of these spaces, among other aspects. Among the materials tested, the maximum increase in height of the water varied between 1 and 145 cm and, although many materials can present capillarity, not all present good potential for the construction of UWDs.

Papers and fabrics, no doubt, were the materials that presented the best results, despite the results varying greatly for each of these materials (Silva, 2013; Zhu et al., 2015; Vasconcelos, 2016; Azeem et al., 2017). For example, in certain types of cotton, the maximum height of the water column elevated through capillarity reached 54 or 56 cm, while, in certain types of microfiber fabrics, it reached 145 cm.

Probably, an onsite use of irrigation through capillarity in ecological restoration, forestry or agriculture that elevated water taken from layers situated 40, 60, or 80 cm below the soil surface would be, in most cases, sufficient. Since the materials tested were not originally developed for the purpose of capturing, conducting and releasing water, it seems probable that, with studies already being undertaken, it would be possible, in the near future, to irrigate plants with water taken from 2.5 m of depth, or even from deeper layers.

The choice of the ideal material to build an irrigator can vary greatly depending on the intended irrigation, being short or long term, permanent or temporary, etc. However, not only capture, but also transport and release should be considered in the selection of the materials to be used. In field conditions, paper or natural fiber fabrics can by attacked by fungus and bacteria or can be consumed by insects or other animals. Whereas synthetic fibers, by being polymers of different materials (plastics), are not attacked by these organisms. However, there are papers and natural fiber fabrics that can be pre-treated with chemical products and become free from the action of bacteria and fungi. To ensure that UWDs do not become potential sources of pollution, their manufacturing should be done with biodegradable materials that do not release toxic residues.

Building up the irrigator with suitable conducting material to capture the water, it should rise vertically until it reaches the roots.However, if along the ascending path the conductor material is in direct contact with the soil, during the elevation part of the water will be transferred to the soil by capillarity, drastically reducing the final water column height obtained. Therefore, normally to avoid this, the conductive material (eg, a fabric or paper tape) must be placed inside an impermeable material (eg, plastic, laminated or paraffined cardboard).

The isolation serves to avoid water losses during the elevation and to internally retain the water vapor evaporated from the conductor material, heavily favoring the elevation of the water column (Figures 1 and 2). To use a ZE irrigator, it is not necessary to alter the production practices of nursery seedlings, since it can be made separate from the seedling and only be connected to the clod and to the seedling roots shortly before they are placed in a new pit or planting furrow (Figure 1c). The water capturing depth is defined by the interest of the planter and by the materials employed in the construction of the UWD (Figure 1).

The last step of the irrigation process would be the transfer and release of water directly to the roots or in their proximity.

Different materials have different capacities to release the captured and elevated water, with some materials being better and some worse at this process. In this way, it is possible to build a capillary irrigator that captures, elevates and releases water made of only one material, or combine distinct materials to optimize each part of the irrigation process.

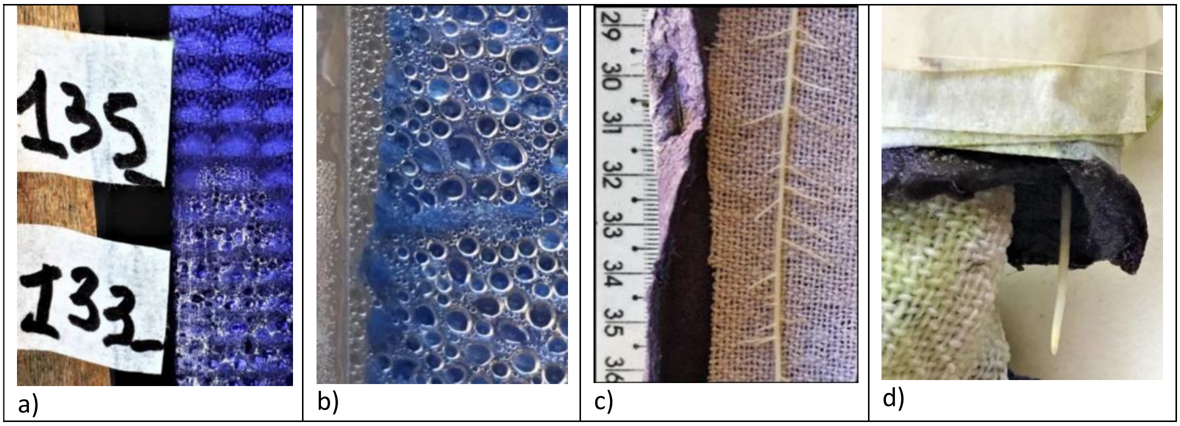

Figure 2: Details of a DA irrigator. In a) rising flow of water inside the irrigator. It can be observed, by the water condensation, that the water column has already reached a height of 135 cm, while the fabric above remains dry. In b) condensed water on the fabric strip, a condition that favors the elevation of the water column and rooting into the fabric. In c) irrigator with no cover to show the rooting on the cotton fabric strip. In d) view of the end of the root of a seedling, and of the fabric exiting through the lower end of the isolating tube.

It is important to remember that the ascendant flux will cease: when there is no more water in the soil level where the capture is occurring; when the water can no longer be extracted from the soil particles; when the irrigating material losses contact with the soil; or if the irrigating material decomposes. If the soil at the capture point dries, the irrigation is disrupted, but if this material used for capture (eg., fabric) does not decompose, when the soil becomes sufficiently wet, the capillarity will reinitiate and the irrigation will happen once again.

I developed two types of irrigators for capillary irrigation in fields. The first, designated ZE, is designed to produce continuous irrigation, with water extracted from the deepest layers of the soil, which is elevated to the roots or to the soil near them (Figure 1c and 3c). For quick and short duration irrigation, a ZE irrigator could be made only using paper, surrounded by impermeable cardboard that then would decompose in situ. However, using fabrics, such as cotton, the irrigation could last months, and with microfibers, possibly years.

The second type of irrigator, designated DA, was developed to avoid irrigation interruptions when the soil in which it is placed dries at the capture point (Figure 2).

In the DA irrigator, it is necessary to change the method of producing seedlings in the nursery. The roots of a seedling are placed over one of the points of a strip of the material chosen for capture, conduction or release of water, and then the roots are covered with a little soil, forming a small clod (Figure 3b). The strip and clod are covered with an impermeable tube to maintain the internal atmosphere saturated with humidity, which favors the elevation of the water and the growth of the roots on the strip (Figures 2 and 3). After, in the nursery, the free end of the strip is placed in a water source and this setup if left in shaded conditions for some weeks. With time, some of the roots grow and colonize the clod and others will descend in the direction of the water source, entrenching themselves in the strip (Figures 2c and 3b). As desired, the long roots can reach 40, 50, 60 cm or more, with it being possible to accelerate this process with small adjustments (Figure 3c).

When the roots reach the desired length, this setup is taken to the field and introduced to the soil (Figures 2d and 3b). To avoid damaging the long roots, during transport and planting, the strip should be maintained covered by the same isolating tube used in the nursery or by another which guarantees this protection (Figure 2). Inserting the DA irrigator in the soil, in a few minutes, from the point of the irrigator, in direct contact with the soil particles and the existing humidity, the water starts to be captured and elevated to the long roots, which then begin to absorb it.

In a DA irrigator, the water coming from the soil rises through the strip and is made available to the long roots and to the surface roots in the clod. Ideally, the isolating tube protecting the irrigator decomposes quickly and easily, after planting, allowing the roots in the clod and in the strip to grow and invade the surrounding soil (Figure 3d).

The main advantage of this irrigator is that the long roots can in short time entrench themselves deeply and begin to obtain water in layers below the maximum depth at which the irrigator was placed, becoming independent from it (Figures 2d and 3d). In other words, even as the soil at this maximum depth dries over time, the plant can continue descending through the soil profile and obtaining water below this planting point (Figure 3d).

In this second case, the irrigator would actually be more a vehicle of deep rooting that would permit the plant to withstand summers or periods of untimely drought.

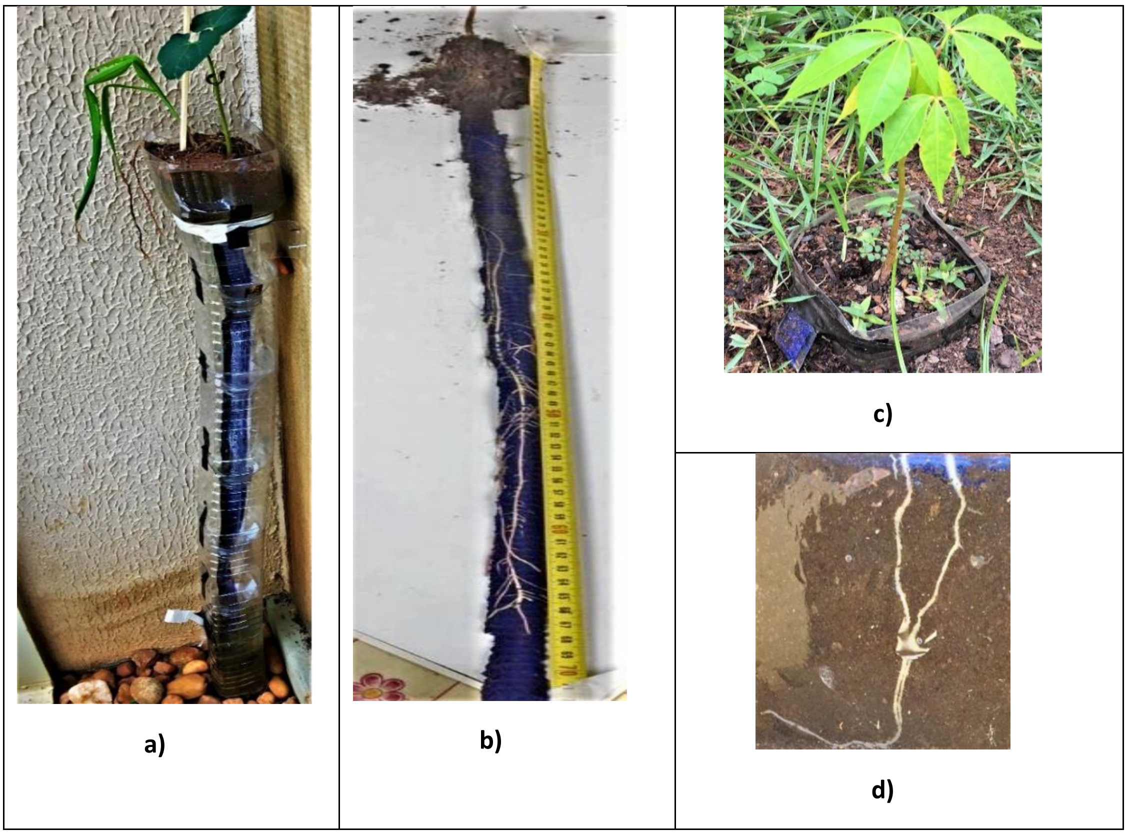

Figure 3: Detail of two types of irrigators. In a) a ZE type irrigator built inside a transparent column to permit observation of the rising flow of water from the soil to the roots of the corn and bean planted one meter above. In b) a DA irrigator without protective cover to allow observation of the seedling clod and roots entrenched in a microfiber strip, with 68 cm of length. In c) detail of a simple test made with a forest species seedling, potted and placed in the soil, but which did not receive water. In this case, a ZE irrigator placed laterally (visible in the picture) transferred water from deep soil layers to the soil and plant. In d) detail of roots that grew outside a DA irrigator that had been placed in the soil only 12 days. The end of the strip can be seen in the upper part of the picture, used to capture water from the soil from where the long roots exited, promoting a deep rooting. In this case, in a few days the plant begins to capture water and nutrients from deeper soil layers than that achieved by the irrigator at the initial planting. This allows the plant to initially benefit from the water that rises by capillarity through the strip, but also with time, it begins to capture from below the end of the strip, allowing the irrigation to persist even if the soil dries at the end of the irrigator.

Although this second type is more expensive, takes longer to build and is harder to put in the field, it can be more secure and efficient than the first, with the choice of the model to be used depending on the intended objectives in each specific case.

One important difference between traditional irrigation systems and those discussed here is that the output of water obtained is slow and continuous, but the flow is limited by the irrigating material. However, after planting, the plant roots are not restricted by the irrigators, since they can and should grow outside the irrigator or deepen in the soil.

The DA irrigator, by favoring an easy deep rooting, would permit that this initial output limitation would no longer be a restriction. At the moment, studies prioritize the optimization of materials, planting procedures and long term monitoring in the field, in a way that, in short, obtains simpler technologies that are of lower cost and easy to access.

Hopefully, in future restoration projects in places where irrigation is necessary, the adoption of these auto-irrigation technologies for seedlings in the field can help reduce the risk of mortality for recently-planted seedlings, favoring their establishment, survival and growth, in addition to allowing for plantings throughout the year. However, many advances can and should be made to make this technology cheaper and more functional. For example, as capillary irrigation depends on the moisture present in the deep layers of the soil and how this water availability varies over time. Better ways to estimate what is the lower limit that the moisture in the soil drops over a year need be created, in order to better allocate the depth at which the irrigator must capture the water, thus guaranteeing a permanent flow.

Obviously it will also be necessary to estimate the impact of this system on the groundwater to guarantee an adequate annual replenishing, allowing for a sustainable and rational use of the water, without risks of degradation.

In theory, the eventual placement of fertilizers on the strips would also allow for direct fertilization of the roots and not the soil, optimizing the fertilizing process and reducing the risks of excessive fertilization and contamination of the soil, groundwater and rivers. An eventual use of the strips with selective capacity could possibly allow for their use in salinized or contaminated soils and, eventually, the application of this technology in bioremediation strategies.

Although this technology was originally conceived for ecological restoration projects, an adequate adaption of its use, on a large scale, in forestry and in agriculture, could contribute significantly to the solution of various environmental problems. Among them are the reduction of erosion and the decrease of the removal of water from water bodies, with a subsequent reduction in water pollution and an increase in water availability for public water supply, industrial use, electrical energy generation, navigation, and fishing, among other activities. This possibility of an optimized and low cost irrigation, facilitating access to irrigation for poor populations, can help reduce socioeconomic inequalities, poverty, hunger and malnutrition, especially if it is available to low income farmers in semiarid regions that may have water under their feet, but no way to obtain it.

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