Using Living Materials to Intervene in the Natural Succession Process to Accelerate the Re-Development of a Self-Sustaining Ecosystem that has been Damaged by Human Intervention

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Abstract

If an ecosystem is severely damaged due to human actions such as over farming, overgrazing or pollution, then the ecosystem will recover slower or not recover at all when compared to the recovery of an ecosystem from a natural disaster. Deforestation causes land in many parts of the world, especially in poor communities, to become less productive, which can have devastating consequences for people who make their living from the land. The use of living materials to jump-start the process of succession in ecosystems damaged by human intervention is studied in this project with the goal of reconstructing a self-sustaining environment more rapidly. Ecosystems are interconnected webs of life, and human interaction with one aspect of an ecosystem can affect the ecosystem as a whole. A plant's interaction with water is studied starting with the root intake of water, then following the water through the stems of the plant to the various organs, and finally out through the leaves as transpiration. A better understanding of the interaction of plants and water in a natural ecosystem can lead to plants being used more effectively to prevent or reduce the effects of deforestation. The water absorption of a perennial shrub, the Golden Yarrow, was studied then studied. Six-inch Irrometer Model R Tensiometers were placed next to the roots to measure the soil tension as the roots extracted moisture from the soil after a three day period of rainfall that resulted in about an inch of rain. The results from the pots with plants were then compared to pots under the same conditions except without a plant in them. The soil tension ranged between about began around 0 kPa, when the soil was saturated with water, to about 30 kPa. Plants had a statistically significant affect on the soil moisture, and the readings averaged about 10 kPa higher for the pots with plants in them. This data can be used to better understand the effects of individual plants in ecosystem restoration projects. Further, long-term testing is recommended to study the effects of a plant on water absorption over a complete season or over the lifetime of the plant.

Background Information

As the human population of the world approaches seven billion people, utilizing the resources available to us efficiently and in a way that doesn't negatively impact the environment is becoming increasingly important. Economies throughout the world are driven by consumption; however, in some cases our consumption is depleting natural resources faster than they can be regenerated and causing serious damage to the environment. According to some sources, humanity is currently consuming resources faster than the earth can produce them. By measuring the ecological footprint, which converts all consumed resources to a figure representing the area of land required to generate those resources and dispose of the wastes, we find that the global average is 2.9 hectares of productive land used for each person. However, only 2.2 hectares are available.[1] The United States averages an astonishing 12.2 hectares per person, which leads to the conclusion that our society and humanity are headed towards self destruction unless we can reorganize our consumption to stay within the ranges that can be sustained by nature. Furthermore, when our consumption or method of production negatively impacts the environment around us, the consequences become even greater because the environment might not be able to generate resources as quickly or at all if it is permanently damaged.

For thousands of years, human beings have been able to use their intellect to alter the environment around them to make survival easier. However, if the environment is altered too drastically, then ecosystems can be permanently damaged, making them less productive at regenerating the resources that we have become dependent on for survival. Many environments around the world have experience deforestation due mostly to economic pressures that often push for more profitable (and likely shorter term) uses of forested land. In some South American and African countries, deforestation can be mostly attributed to poor subsistence cultivators. The rural poor will burn areas of the rainforest to make room for farming. Unfortunately, these farming techniques, called "Slash and Burn Farming", often do not provide farmable land for more than a few years because without the forests the land is depleted of nutrients rapidly. Therefore, the farmers must clear new areas of forest every few years in order to continue providing food for their families and communities.

However, deforestation is not always caused by poor slash and burn farmers. For instance, in the Brazilian Rainforests, over 600,000 square kilometers have been destroyed since 1970, and much of that deforestation can be attributed to land clearing for pastureland by commercial interests, misguided government policies, World Bank projects, and other commercial exploitation of forest resources.[2] About 60 to 70% of the deforestation in Brazil is attributed to cattle ranches that clear large sections of forest and sometimes plant them with African savanna grasses for cattle feeding. At times, pastureland prices have exceeded forest land prices due to tax incentives that favor pastureland over natural forest. In these cases,

government support of economic expansion has given cattle ranchers and incentive to clear more land, and forest land is sometimes cleared as an incentive (Figure 1).

Figure 1: Forest cleared for cattle ranching in São Félix do Xingu, a municipality of Brazil with one of the largest areas of rainforest left in the Eastern Amazon.[3]

Not surprisingly, the Brazilian deforestation is strongly correlated to the economic health of the country. Brazil's economic slowdown from 1988-1991 nicely matched the decline in deforestation during that period. Similarly, the high rate of deforestation from 1993-1998 coincided with a period of rapid economic growth in Brazil.[2]

Deforestation is not limited to the tropical rainforests of South America and Africa. The Loess Plateau region in the Gansu Province of China has experienced extensive deforestation. This area of China is home to about 40 million people, most of who are herders or farmers of traditionally potatoes, beans, and maize.[4] The natural climate of the Loess Plateau region makes it susceptible erosion. The soil is silt-like and can easily be washed away by heavy rainstorms, and heavy rainstorms are relatively common in this region. Almost all of the years rainfall, which is between 8 and 22 inches, usually falls between the three months between July and September, and up to 40% of the total rainfall has been known to occur in a single rainstorm.[4] While these environmental factors certainly contribute to the extensive erosion and deforestation, environmental factors alone could not have caused the situation that exists today. Famine, poverty, and population pressures caused the inhabitants to expand their farming to more marginal farmland, land which was more susceptible to erosion.

Years of poor farming techniques and over grazing has caused the soil to become depleted of nutrients in some areas, which lead to decreased plant life. The combination of environmental and human factors in the Loess Plateau region has lead to some of the world's most extensive erosion due to deforestation (Figure 2).

Figure 2: Extensive erosion in the Loess Plateau region of China has been caused primarily by human intervention.[5]

Reforestation efforts in the Loess Plateau region have been undertaken by the Chinese government with limited success. Government corruption and the unwillingness of the inhabitants to give up farmland have slowed the reforestation efforts.

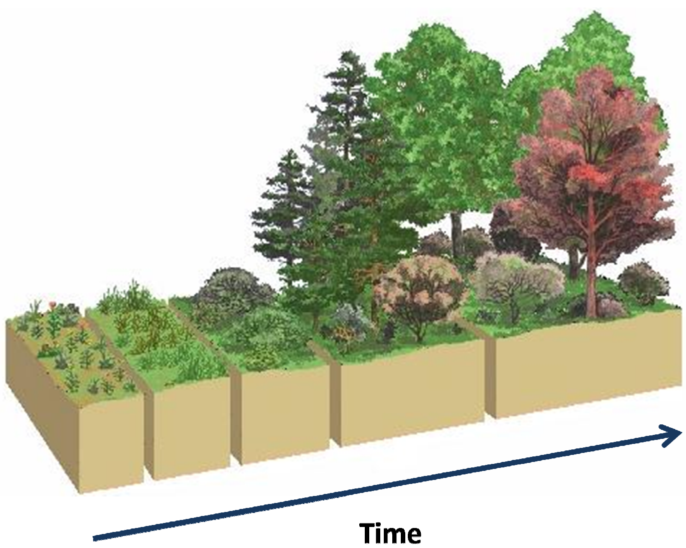
Deforestation in any part of the world often accelerates rapidly due to cyclical effects. Human intervention, such as poor farming techniques or over grazing, leads to an environment with depleted nutrients, and less native vegetation is able to grow. Fewer plants means less rainfall is absorbed by the vegetation, which leads to increased run-off and more erosion. In addition, less vegetation often creates more unstable weather patterns because less water vapor will be released through leaf transpiration, which can lead to more inconsistent rainfall. Increased erosion and inconsistent rainfall lead to greater losses of soil nutrients and less native vegetation. The cycle of deforestation continues and the vegetation is decreased year by year. The short term gains made by extensive farming or the profits made by increasing the size of pasturelands, is outweighed by the long term consequences of deforestation. In cases of extensive deforestation, often the inhabitants are left with nutrient deficient soil that is unfit for farming or grazing, and they are forced to either move or face starvation.

In order to attempt to prevent and reverse the damaging effects of deforestation, the interconnections of the natural ecosystem and the natural process of environmental repair, or succession, must be studied.

Natural Succession

The various stages of repair that an ecosystem goes through after a disaster in order to reach its most productive state are called succession. Even if an ecosystem is almost completely

destroyed by a natural disaster, such as a fire, volcanic eruption, or flood, in most cases the environment is able to recover and regain its former productiveness. When an ecosystem is damaged by a natural disaster, the disaster itself often provides benefits that allow the succession process to begin. For instance, a volcanic eruption might destroy most or all of an ecosystem, but volcanic ash is rich in nutrients and any surviving seeds or seeds carried by winds or birds will be able to use those nutrients to grow quickly. Similarly, fires leave behind fertile ash and clear space for new seedlings to grow. Some ecosystems, such as those in Southern California, rely on periodic fires to clear deadwood and provide space and nutrients for seedlings to grow, and some seed pods will only release their seeds after they have been burnt by fire. With the initial jump-start left behind by the natural disasters, ecosystems are able to go through a series of changes, starting with mosses or small annual plants, and in most cases building towards some type of forest (Figure 3).[6] Figure 3 shows a typical succession process from small annual plants starting on the left, to perennial plants (plants living two or more years) and grasses, to larger shrubs, to a young pine forest, and finally to a mature oak-hickory forest on the far right.



ss from small annual plants to

Each stage cannot take place without the stage before it because each additional stage lays the foundation for the stages to come. For instance, annual plants can grow in less nutrient rich soil conditions than perennial plants can grow in. As annual plants die off, they are decomposed by bacteria, fungi, or other micro-organisms and nutrients are added to the soil. Similarly, perennial plants have more extensive root systems and can support more micro-organisms and more small animals, which leads to more soil fertility and paves the way for larger shrubs. Ecosystems can be thought of as an interconnected web, where all the plants, animals, organisms, nutrients, water, and soil all play important roles. If one part of an ecosystem is destroyed or not able to function correctly, then the whole ecosystem will likely be adversely affected. Also the same idea holds true for the process of succession because if one of the stages of succession does not take place, then the ecosystem is unlikely to be able to continue to the following stages of succession.

The time frame for succession depends on the ecosystem in question and the extent of the damage that it suffered due to a natural disaster. In addition, a recovering ecosystem will be

building towards its peak productivity, or the most plant and animal species that can thrive in a given environment. The peak productivity will be different for each ecosystem depending on factors such as soil condition, topography, weather conditions, and seasonal changes. For instance, in the Amazon near the equator is a rainforest. In Australia, the most productive environments are grasslands or Eucalyptus forests. On the coast of California, the most productive ecosystems are oak forests or grasslands, or redwood forests in northern California. Some experts argue that ecosystems never actual reach this peak productivity, or climax, because they are periodically interrupted by natural disasters. Many ecosystems may be thriving to reach a climax productivity, but never actually get there.

When an ecosystem is damaged by human interactions, the environment is often left without benefits left behind by a natural disaster. Therefore, sometimes ecosystems are left without a jump-start into the succession process and are unable to recover or recover much more slowly than when damage by a natural disaster. In addition, sometimes human interaction with a particular environment continues to damage the ecosystem over time, which makes the succession process more difficult. If the damage caused to an environment by humans is severe, then the cyclical effects of deforestation can cause the land to become uninhabitable. Without enough nutrients to support most plant life, the rainfall will not be absorbed as well and environments that were once rich with plant and animal life can turn into deserts will few plants and animals able to survive. This type of desertification is devastating to humans living in that environment.

Intervention for Deforested Areas

If a community is faced with the problem of deforestation, which makes agricultural production much more difficult, it is tempting to turn towards high-tech advances and in some cases short-term solutions. For instance, if the soil is lacking nutrients, it might be tempting to use stronger fertilizers or to expand to new areas for agriculture. However, solutions such as these will often only provide temporary solutions and may cause more damage to the environment in the long run. A more permanent solution can be obtained by studying healthy ecosystems and the succession process. By planting a combination of usually native plants and putting down mulch that will facilitate the growth of fungi and other organisms, some areas that were previously desert have been partially reforested.

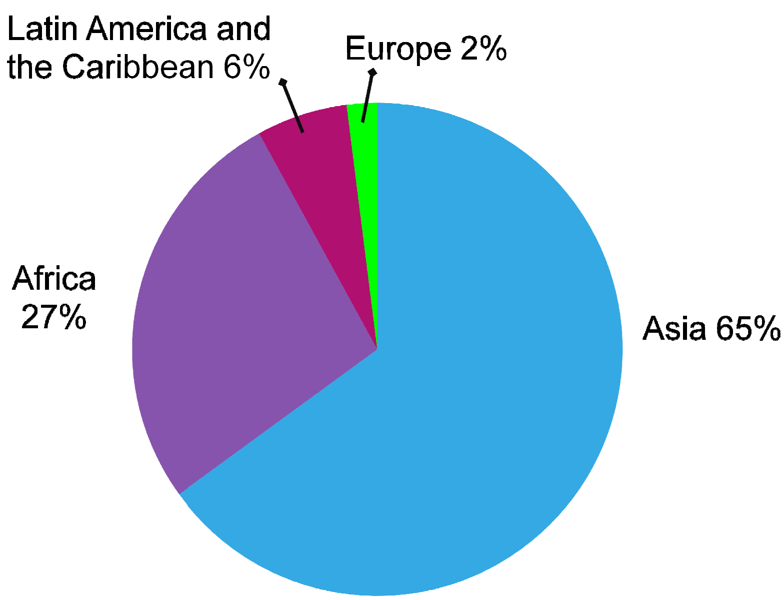
For example, Geoff Lawton and his colleges demonstrated how to rebuild soil that was previously thought to be unusable for agriculture without the extensive use of synthetic fertilizers.[7] He used permaculture techniques, or techniques based on replicating the natural environment, and showed that the infertile, salty soil of a desert in Jordan could be transformed into conditions favorable for agriculture. They planted a combination of trees and shrubs, utilized organic matter and the natural organisms that thrive in the organic matter, and carefully

controlled water resources using swales (irrigation troughs that follow the natural topography of the environment). And they showed that the high levels of salt in the soil could be reduced to a level that allows plant growth without the addition of fertilizers.

Water Management

In this and other reforestation projects, water management is one of the most important factors in the success of the project. Even badly deforested areas still have some rainfall, and that rainfall must be absorbed and kept in that area to reduce the negative effects of erosion and to allow the plants to live. Water is one of the most important resources to the survival of all life on earth, and as population pressures continue to increase water needs world-wide are continuing to increase. In many of the communities affected by deforestation, the community often does not have extensive water resources that could be used in a reforestation project.

Only 2.5 percent of the planet's water supply is fresh, and much of that is locked away in glaciers. Many people in less developed countries are currently struggling in many cases to have access to clean drinking water. And this problem might only be getting worse because the world water use in the past century grew twice as fast as the world population.[8] In addition, according to a United Nations study committee, the distribution of people who don't have access to adequate water supply daily are concentrated mostly in the developing world in Africa and Asia (Figure 4).[9] According to this study, 1.1 billion people are considered to not have adequate



/ daily.

access to water. Not having adequate access to water is defined as not having at least 20 liters a day of contamination free water for washing, cooking, and drinking.

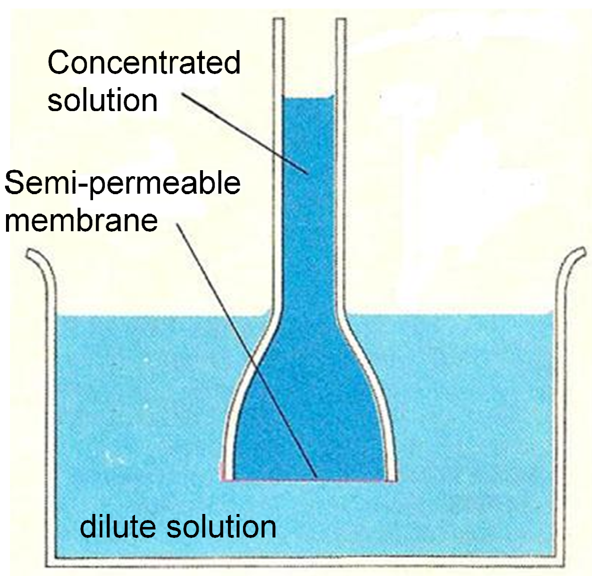
Project Goals

Living materials have been successfully used in reforestation projects to reverse the adverse affects of deforestation. This project focuses specifically on increasing the water absorption in deforested areas by using living plants. In a functioning ecosystem, plants function to retain the water received from rainfall or other sources; however, in a deforested environment plants can be used as intervention to arrive at a solution for deforestation. The structure and properties of plants will be analyzed in order to determine their performance in terms of their ability to retain water and offset desertification.

As mentioned earlier, ecosystems are interconnected webs and the succession process depends on the plants, animals, micro-organisms, soil, nutrients and water. However, in order to fit within the scope of this project, all the interactions cannot be at once. In this project, the interaction of plants with water will be primarily studied, even though many other factors go into successfully reforestation of an environment. In order to understand how a plant retains water, the path that water takes through a plant must first be understood, starting with the roots.

Root Intake of Water

Plants take in water through diffusion across a semi-permeable membrane, which is called osmosis. In a typical osmosis setup, a dilute solution (mostly water) surrounds a container of more concentrated solution (less water), and the solutions are separated by a semi-permeable membrane (Figure 5).[10] If the membrane is permeable only to water, then the water will flow from areas of high concentration to areas of low concentration because diffusion is driven by concentration differences. Therefore, in this model the higher concentration of water in the outside container will cause water to flow spontaneously though the membrane and into the more concentrated solution that contains less water, which will cause the water level inside concentrated container to rise. The spontaneous movement of water in this case down the concentration gradient is a passive diffusion process because no input of energy is required.



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Cells in the roots of plants take in water in a similar way to the pervious osmosis model. The root cells will create a higher concentration of ions inside the cell by taking up ions, such as nitrate (NO_3^-). There will then be a higher concentration of water outside the cells in the soil than there is inside the cell. The water will then spontaneously flow from the surrounding soil, through the semi-permeable membrane that will allow water in, and into the root cells of the plant.[11] Since the water spontaneously flows into the roots, the diffusion of water is a passive process; however, this process is indirectly energy depended because a plant must use metabolic energy to transport ions into the cells.

Plants must use an input of metabolic energy to actively transport ions and other nutrients into the root cells. Energy from the sun is captured during photosynthesis, and that energy can be used to transport ions and other nutrients actively. Plants take in carbon dioxide, water, and light energy and produce glucose, water, and oxygen (Eq. 1).

Eq. 1: $6\,CO_2(g) + 12\,H_2O(l) + \text{Photons} \rightarrow C_6H_{12}O_6(aq) + 6\,O_2(g) + 6\,H_2O(l)$

The plant then uses enzymes to break down the high energy glucose molecules ($C_6H_{12}O_6$). Some of the energy released is used by the plant to do work, and the rest of the energy is captured and stored in the molecule Adenosine Triphosphate (ATP). ATP has three high energy phosphate bonds (Figure 6).[12] The three phosphate bonds have negatively charged oxygen atoms that are situated close together, and the oxygen atoms repel each other, which creates potential energy.[13]

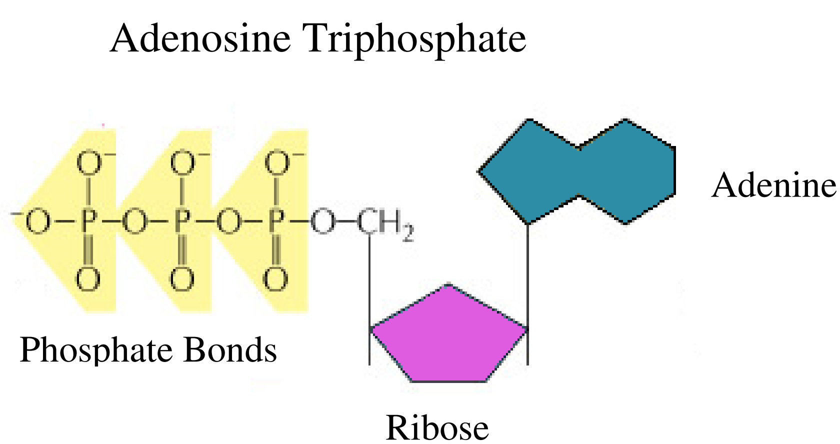


Figure 6: Adenosine Triphosphate molecule showing three phosphate bonds.

When the cells need to use metabolic energy to transport ions, the cells use special enzymes to break off one of the high energy phosphate bonds of ATP to form Adenosine Diphosphate (ADP). The energy released is used in active transport. The cell can later use energy from the breakdown of glucose molecules or other sources to reattach the phosphate bond and store energy again in the form of ATP.

The Role of Bacteria and Fungi

The intake of ions and other nutrients by the roots of a plant is not as simple as simply extracting those nutrients from the surrounding soil. Ecosystems are interconnected webs, and plants often have symbiotic relationships with bacteria and fungi that aid in the intake of ions and other nutrients through the plant's roots. Not all relationships between bacteria or fungi and plants are beneficial to the plant, but some relationships are crucial to the plant's survival. One example of this crucial symbiotic relationship takes place between plants and nitrogen fixing bacteria (Figure 7). This relationship is especially important to the legume family of plants, which includes beans, lentils and peas and is a staple food for many cultures around the world.[14]

Figure 7: Nitrogen fixing bacteria is show attached to the roots of a plant.

The earth's atmosphere is composed of about 79% nitrogen (N_2 gas); however, most plants are unable to utilize nitrogen in this form. The stable triple bond between two nitrogen atoms makes this molecule nearly inert, and plants rely on the reactivity of ions and molecules to utilize them.

The nitrogen fixing bacteria can use special enzymes, called nitrogenase, to produce ammonia (NH_4) or nitrate (NO_3) by breaking down N_2. In return, the bacteria are sometimes protected by plants by keeping them away from oxygen molecules.[14] Some plants contain oxygen-scavenging molecules, which help protect the bacteria's enzymes which become inactivated if they are exposed to oxygen.

The fungus called Mycorrhiza is another example of the symbiotic relationships between plants and micro-organisms like bacteria and fungi. Mycorrhiza branches off from the roots of plants, and is found in about 80 percent of plant species. Because Mycorrhiza branches off from the roots further into the soil, it increases the area that the roots can draw water and nutrients from. Certain types Mycorrhizae also help plants to absorb phosphate ions. Phosphate ions are highly reactive in some soil types and will combine with other elements to form insoluble compounds that cannot be taken in by plants.[15] Mycorrhiza can break down these compounds and make phosphorus ions more available to plants. Plants provide the Mycorrhiza with carbon that aids in growth and development.

Water Conduction through Plants

Once water has been absorbed by the cells in a plant's roots, the water must then travel up through the stalks of the plant to the leaves. The water diffuses through layers of cells to the center of the roots, where the water enters vascular tissues. Vascular tissues, made up of different tissues called the xylem and phloem, conduct water and nutrients between the various organs of a plant.[11] The xylem is primarily responsible for the transport of water, dissolved minerals, and sometimes small organic molecules upward through a continuous system into the branches, leaves, flowers, and fruits. A cross-section of a typical plant root shows the various plant cells with the xylem cells creating a network in the center of the root (Figure 8).

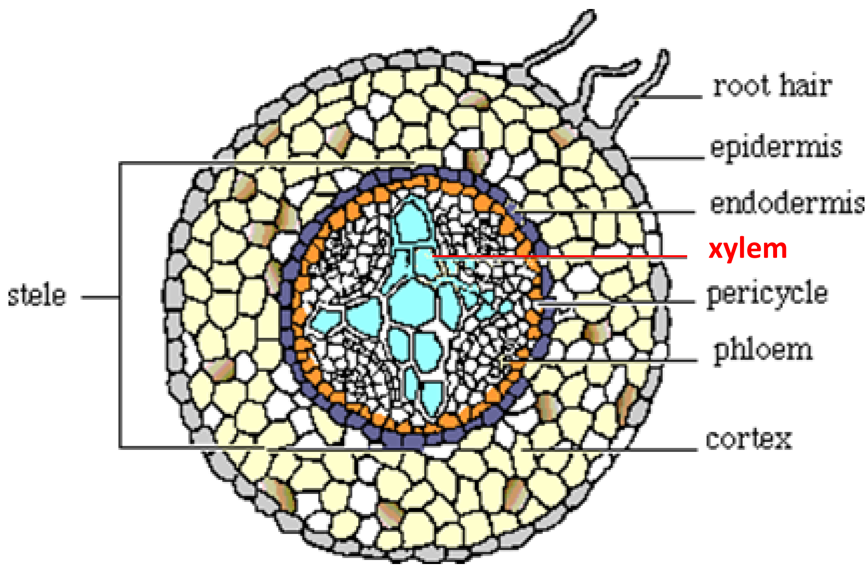


Figure 8: A cross section of a root showing the xylem tissues highlighted in light blue in the center.[16]

Tracheids and vessels that make up the xylem are composed of an interconnected network of elongated cells that are non-living once they are mature and functioning. There are three ways in which plants are able to resist the forces of gravity to transport nutrients and water from the roots to the leaves at the top of the plant.

As discussed in the earlier section on the root intake of water, roots actively transport mineral ions from the soil, which are then actively transferred to the xylem. The intake of ions will cause water to flow from higher concentrations outside the plant to lower concentrations of water inside the xylem. The spontaneous flow of water into the xylem creates a pressure that pushes the water up into the stem of the plant.

The next reason that plants are able to transport water against gravity is due to the structure of the vascular tissues and the interaction between the insides of the tissues and the water molecules. Vascular tissues can be thought of as a long tube with a small diameter that

extends up into the plant. The water will rise up the plant without any input of energy due to Capillary rise. Capillary rise can be seen if a tube with a small diameter is inserted into a volume of water (Figure 9). The water will rise up the tube until the forces are balanced by gravity.

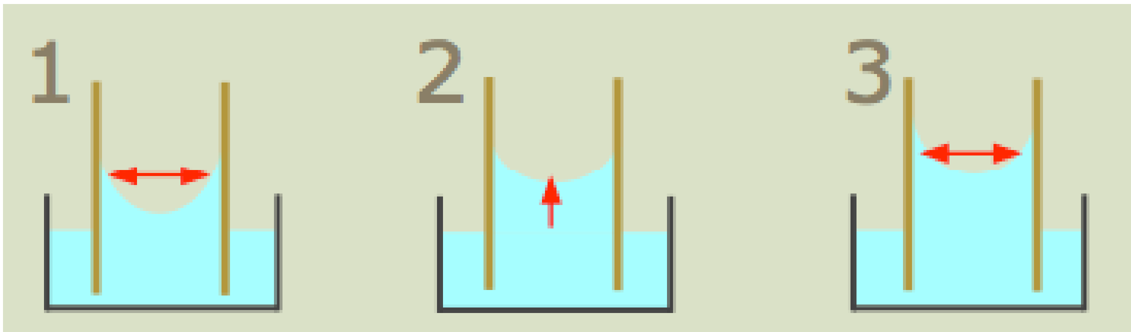


Figure 9: The forces of capillary rise are shown drawing water up the inside of a small diameter tube.[17]

In picture 1 in Figure 9, the water around the edges of the tube is drawn upwards by strong adhesion forces between the walls of the tube and the water molecules. When the water on the outside of the tube is drawn up, the water in the center of the column will be pulled up because of the surface tension of water, which is shown in picture 2 of Figure 9. The surface tension of water is due to its structure, which is made up of two hydrogen atoms and an oxygen atom. The negative charge of the oxygen atom and the partially positive charge shared between the two hydrogen atoms make water a polar molecule. The separation between the negative and positive charges creates strong attraction forces between water molecules due to hydrogen bonding, and strong attraction forces between molecules creates a high surface tension. The high surface tension of water will cause the center of the tube to be pulled up because the water wants to minimize its surface area.

After the center of the column rises to catch up to the water on the outside of the tube, the adhesion forces between the sides of the tube and the water will again pull up the water on the outside of the column. The process will continue until the height of the column is balanced by gravity. Vascular tissues can be modeled as long tubes with small diameters, and the adhesion between the inside of the xylem cells and water is strong.[11] If a plant has xylem tissues that form a column with a diameter of 50 microns, which is typical for some small shrubs, the water would rise about 60 cm high due to capillary rise.

Active transport of ions causing upward root pressures and capillary rise can account for the most of the water movement in small plants; however, in larger bushes and trees, these forces alone would not be sufficient to transport water to the leaves and other organs at the top of those plants. A third explanation of how water moves up through a plant is needed to explain the forces required to transport water to the tops of trees and large bushes. Cohesion theory models the plant as a continuous column of water and nutrients from the roots to the leaves, and this

continuous column can be pulled up because of transpiration, or release of water vapor, from the leaves. As water evaporates from the leaves, a tension is created that pulls water up the stalk of the plant (Figure 10).[18] The blue arrows in the figure represent the flow of water from the roots out through the leaves of a plant. The faster a plant transpires, the more rapidly water will be drawn through the plant. In rapidly transpiring trees, tensions of 0.5 to 2.5 MPa have been recorded.[11]

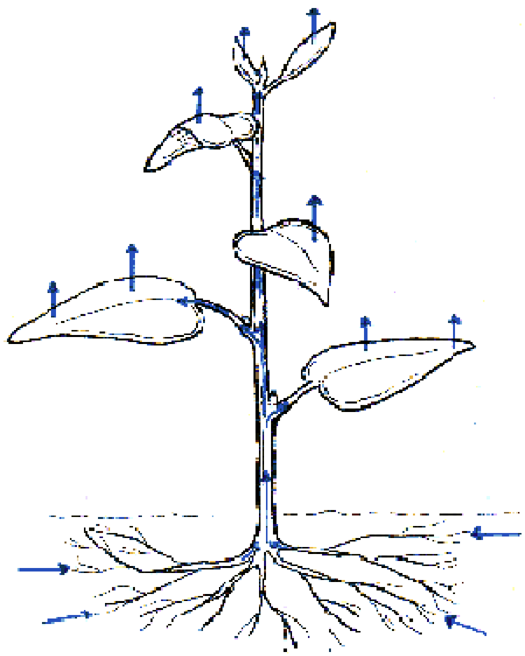


Figure 10: Water flow shown through a plant from the roots out through the leaves.

Cohesion theory is now generally accepted as one of the explanations for water movement through plants. However, when it was first being discussed, one of the difficulties in accepting the theory was that it requires that a continuous column of water be present. If the column was interrupted by gas bubbles or broken for any other reason, then the tension would not reach all the way to the roots and water would be unable to move through the plant. Maintaining a continuous column of water through the plant is difficult because the water is carrying dissolved gases and other solvents to areas where they are needed throughout the plant. Dissolved gasses like carbon dioxide, oxygen, and nitrogen that are carried through plants have a tendency to come out of solution when they are under tension as they are in the plant. In addition, if a plant goes through a freeze-thaw cycle, then pockets of gases can form because the solubility of these gases in ice is lower than in water.

These gas bubbles formed inside the xylem vessels have the potential to break the continuous column of water and prevent water from reaching the top of the plant. In order to prevent the column of water from being interrupted, the structure of the xylem cells is used to trap air bubbles if they are formed and allow water to pass around them. The xylem vessels are made up of elongated cells, and if an air bubble is formed in one of the cells, the cell will shut itself off from the continuous column of water, and water will be able to travel around the cell with the trapped gas bubble through the surrounding xylem cells. The cells trap air bubbles because a bubble filled with gas will have a pressure difference compared to a bubble filled with water and dissolved solvents. The pressure difference will cause a region of the membrane between cells, called a torus, to close off the pathway between the cell with the trapped gas and the cells around it.

Plants are able to recover the cells that have trapped gases when transpiration lessens. Transpiration lessens greatly at night, and this reduces the tension felt by the column of water inside the plant. Therefore, gases that have been trapped by xylem cells are often able to re-dissolve back into the water column at night because of the reduced tension.[11] In addition, some evidence suggests that plants are able to recover from having trapped gases in some of their cells during spring time growth periods.

Leaf Transpiration

We have now discussed how water enters through the roots and is transferred through the plant's stems to the leaves; the next step is to discuss how and why leaves transpire. As water travels in the xylem vessels to the leaves, the vessels branch out into smaller vessels to transport water to all areas of the leaves. The leaf structure allows for transpiration and intake of carbon dioxide through the stomata (sg. stoma) openings (Figure 11).[19] The cuticle is a waxy layer that prevents evaporation of water from the cells on the top layer of the leaf, called the epidermis. The thickness and continuity of the cuticle determines how much water is evaporated from the top of the leaf. In a desert environment, where water must be conserved carefully, most plants have thick cuticles that prevent almost all evaporation of water from the top of the leaf.

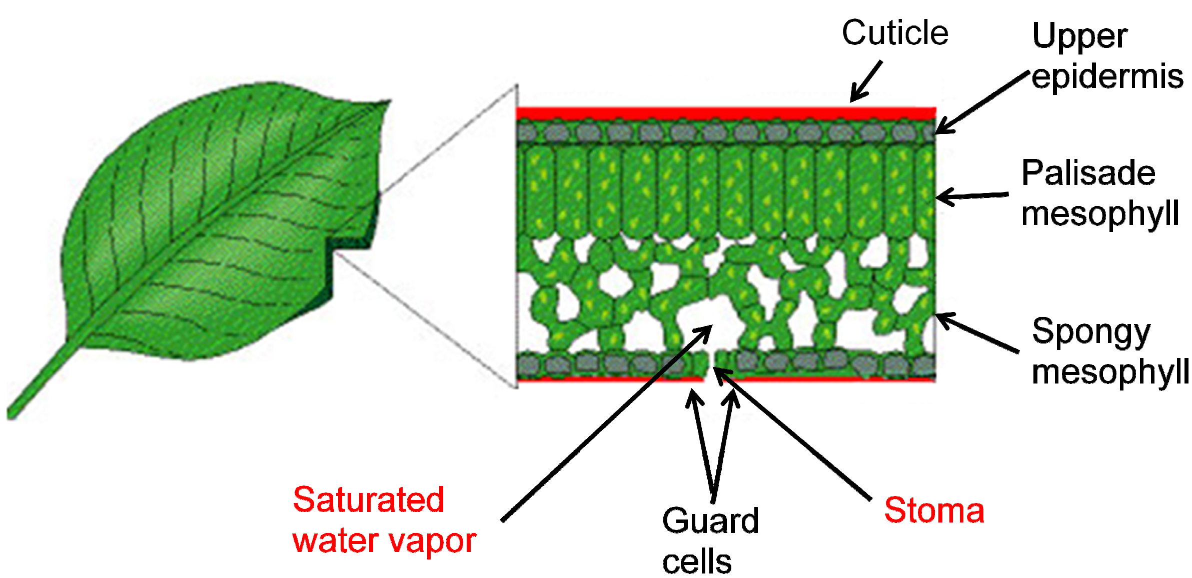


Figure 11: The structure of a typical leaf showing a blown up view of a cross section of the leaf.

The layers of mesophyll cells, which are cells that are involved in photosynthesis, are highly ordered at the top of the leaf in order to efficiently absorb sunlight. However, towards the bottom of the leaf, these mesophyll cells are loosely arranged leaving open spaces. On the bottom of the leaf, the cuticle layer is interrupted intermittently by small pores called stomata. The size of these

pores is controlled by cells on either side, called guard cells. The guard cells can expand or contract to adjust the size of the stomata.

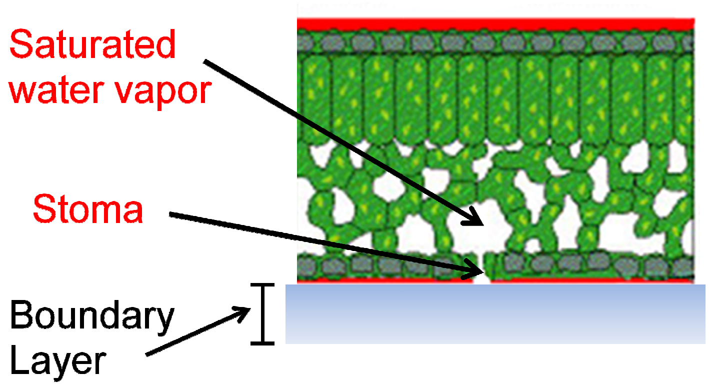
Water is transferred from the xylem vessels to the mesophyll cells. When the mesophyll cells are adjacent to the open spaces, the water will evaporate from the cell and form water vapor in the small open spaces. Since water is continuously flowing through the plant, water is continuing to be transferred to mesophyll cells and continuing to evaporate. Therefore, the vapor inside the open spaces is considered saturated water vapor.[11] 90 to 95 percent of the water absorbed by a plant is released through transpiration, and almost all of that water is released through the stomata.[11] As transpiration increases, water absorption by the roots must increase in order to maintain cellular pressure and reduce wilting.

The driving force for transpiration is the high water vapor pressure inside the leaf and the lower water vapor pressure outside the leaf. Similarly to the water in the ground moving from high concentration to lower concentration inside the roots, the water vapor in the interior of the leaf moves from high vapor pressure to low vapor pressure down the concentration gradient. The transpiration rate is dependent on wind, temperature, and humidity. The effects of wind, temperature, and humidity can be determined by analyzing Fick's first law (Eq. 2).

Eq. 2 —

Where J is the flux, or the amount of a substance that diffuses per unit area per unit time, D is the diffusivity, and — is the concentration gradient.

Under the leaf, there is a layer of undisturbed air that has a high concentration of water vapor called the boundary layer (Figure 12). The boundary layer profile is affected by the shape of the leaf and by the wind speed. Higher wind speeds shrink the boundary layer, which increases the concentration gradient. The higher concentration gradient leads to faster diffusion and increased transpiration. However, higher wind speeds only increase transpiration to a point because as wind speed increases, the stoma tends to close. Less water vapor will be able to escape from the partially closed stomata. Therefore, wind speed will increase the transpiration rate up to a point until the high wind speed induces



turbed air exists beneath the leaf

the stomata to close.

The temperature inside a leaf is often 5 to 10°C hotter than the surrounding air. Therefore the water vapor pressure inside the leaf will be higher due to the higher temperature. If other factors remain constant, a larger the temperature difference between the inside of the leaf and the outside air will create a larger the difference in vapor pressure. Therefore, the concentration gradient, and the transpiration rate, will increase if the difference between the temperature inside and outside the leaf increases. If the temperature inside and outside the leaf is the same, then a higher temperature will lead to a higher transpiration rate. Increases in temperature of the system as a whole will increase the diffusivity according Eq. 3.[20]

Eq. 3 $D = D_o e ^ (-Q/RT)$

Where D is the diffusivity, D_o is the maximum diffusivity constant, Q is the activation energy for diffusion, and R is the gas constant. A higher diffusivity will lead to a higher diffusion rate according to Fick's first law.

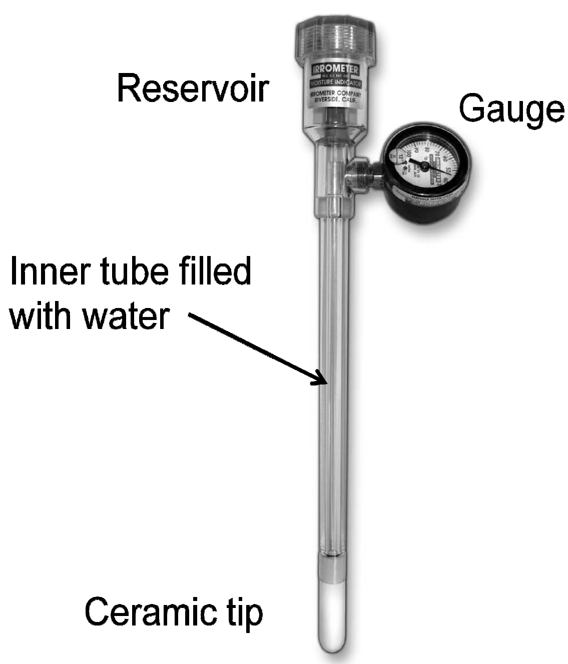
The humidity inside the leaf in the small openings between mesophyll cells can be assumed to be 100 percent because it contains saturated water vapor. Therefore, changes in the humidity outside the leaves will affect the transpiration rate. Vapor pressure outside the leaf will decrease as the humidity decreases. Therefore, a lower humidity outside the leaf will result in a higher concentration gradient between the water vapor pressure inside and outside of the leaf, and a higher transpiration rate. If the humidity outside the leaf is 100 percent, then there would be no transpiration caused by differences in humidity, but temperature and wind factors could still cause some transpiration, as is sometimes the case in tropical rain forests.

Transpiration is a necessary process for plants and helps to recycle water vapor back into the air. Transpiration increases the rate of water movement through plants, and since nutrients and other dissolved solvents travel with the water, transpiration helps to deliver nutrients to where they are needed more quickly. Transpiration also helps to cool the leaves similar to how the human body cools itself by sweating. Cooling is important because in direct sunlight a leaf could overheat if it wasn't able to cool itself by the evaporation of water. In addition, the Stamata openings that allow water vapor to be released are necessary to allow the plant to intake sufficient carbon dioxide to perform photosynthesis. Lastly, plant transpiration plays an important role in stabilizing the environment because it recycles water vapor back into the air that will be able to condense and all again as rain. Without plants absorbing rainfall and recycling it into the environment through respiration, more of the rain would be lost to runoffs that erode away nutrients and cause other destruction to ecosystems.

Testing Plant Water Absorption

In order to study the effects of a plant on water absorption, an experiment was set up to measure the differences in soil wetness between pots with plants and pots without plants. For this experiment, the Golden Yarrow (Eriophyllum confertiflorum) was chosen. The Golden Yarrow is a perennial shrub that is drought resistant and not overly invasive. Also, the Golden Yarrow is native to California and could be a good candidate to reduce erosion because of its strong root system compared to other perennial shrubs.[21] The goal of the study was to determine the effects of planting a Golden Yarrow on the water available in a controlled environment. This information only describes one piece of a complex ecosystem, so further studies will have to be conducted in order to understand the interaction of water within all the plants and organisms of an ecosystem.

For this study, five gallon pots were filled with soil from the same area of one of the farms on the Cal Poly campus. Two pots were planted with Golden Yarrow plants and two were left empty. The soil moisture content of each pot was measured over a period of time using soil Tensiometers (Figure 13). Soil Tensiometers are one of the most accurate ways to measure soil wetness and are often used to calibrate other equipment.[22] Tensiometers measure directly the pressure required to extract water from the soil, which is an accurate measure of how much effort must be expended by a plant's roots in order to absorb moisture. The Tensiometers used in this experiment were the 6-inch Model R from the company Irrometer.



es the pressure required
ramic tip.

Tensiometers are placed in the ground right next to the plant to the depth of the root system that is being studied. The Tensiometer has an inner tube filled with water. As the soil around the Tensiometer dries, water from the inner tube will diffuse out the ceramic tip at the bottom, and a pressure will be created below the reservoir. The pressure is measured by the gauge. A high pressure means that a lot of water has diffused through the ceramic tip because the soil is dry. The gauge runs between 0 and 100 kPa. The meaning of the gauge readings depends on the soil type, but generally readings between 0 and 20

kPa indicate that the soil is saturated with water. The typical use of a soil Tensiometer is to determine irrigation cycles for crops. Each crop will have a different range of tensions that correspond to idea soil wetness for that plant, but many crops will ideally receive irrigation when the soil tension reaches 50 or 60 kPa.[22]

Experimental Setup

In order to determine the effect of a living plant on the water absorption in an ecosystem, this experiment tested the difference between soil moisture for pots with Golden Yarrows and pots with soil only. Soil from the same area of one of the farms on campus was placed in four, five-gallon pots. Two of the pots were planted with Golden Yarrows that had been growing at a nursery for about 2 months. The plants were about 5 inches tall at the time of transplant, and similarly developed plants were chosen. The pots were placed on an outside patio, and the factors such as sunlight, wind, temperature, and humidity were assumed to be constant for the four pots. Super Soil potting soil was placed in the top 4 inches of the center of each of the pots that didn't have plants in them in order to keep the soil conditions as similar as possible for all the pots. In order to transplant the Golden Yarrows successfully, some of the soil that they were originally planted in had to be transferred also, and they were originally planted in Super Soil potting soil.

The soil Tensiometers were soaked in water for three days before use to sufficiently wet the ceramic tips. The inner tube and reservoir were filled with water mixed with green die so that the water level could be more easily monitored. The Tensiometers were inserted at a slight angle into the center of the pots either right around the roots of the plants or at the same depth and location as the roots would have been in the case of the pots with only dirt (Figure 14). Care was taken to ensure that there were no air pockets between the soil and the ceramic tip because that would have resulted in higher readings than there should have been. Before putting the Tensiometers in the ground, any air bubbles were then removed using a hand vacuum pump. Each Tensiometer was pumped to about 75 kPa three times to ensure that all the air bubbles had been removed because any air bubbles would affect the measurements.

Figure 14: One of the pots used with a Golden Yarrow and Tensiometer inside.

Results and Discussion

The accuracy of each of the Tensiometers was determined by using a hand vacuum pump with a vacuum gauge that was purchased along with the Tensiometers. All the Tensiometers had readings slightly lower than the readings on the vacuum pump gauge (Table I). Each Tensiometer was pumped up to about 75 kPa three times and the average differences between the each of the Tensiometers and the vacuum gage measurements are show in Table I.

Table I: Differences in Tensiometers and Vacuum Gauge Measurements

	Tensiometer 1	Tensiometer 2	Tensiometer 3	Tensiometer 4
Average Difference (kPa)	-2.03	-2.2	-1.76	-1.93
Standard Deviation	0.058	0.200	0.251	0.115

Tensiometer 2 had the lowest reading compared to the reading of the vacuum gage with an average reading of 2.2 kPa less, and Tensiometer 3 had the closest reading to the vacuum gage with an average reading of 1.76 kPa less. However, all of the Tensiometers were right around 2 kPa less than the vacuum gauge so the possible differences in the Tensiometers will not affect the experiment because they give such similar readings when tested with the vacuum pump. In addition, the small standard deviations between the different vacuum pump trials, shows that the Tensiometers were consistently giving similar readings from one trial to the next.

Unfortunately, due to time constraints and the lack of success with earlier experiment attempts, the soil moisture was only measured for three days. The experiment was started after a three day period of intermittent rain in which about an inch fell in San Luis Obispo. The rain saturated the soil thoroughly, and the readings for all four Tensiometers were in the 0 range. The gauges of the Tensiometers start readings at 6 kPa. About 2 days after the rains, the Tensiometers began to move out of the 0 range as the soil began to dry out. Readings were taken every two hours from 10:00 a.m. to 6:00 p.m. for the next three days (Figure 15). The drainage from the pots was considered to be negligible because the pots only have a few small holes on the bottom and the patio remained dry. Evaporation from the soils surface took place for all the pots and was considered to be about the same for all the pots. The evaporation rate would be different if the sunlight, wind speed, temperature, or humidity was different; however, since the pots were so close to each other on the patio, these factors were considered to be about the same. In addition, the plant foliage could have blocked some of the sunlight, which would make the evaporation slightly less in the pots with plants. However, since the Golden Yarrows were small and have

small leaves, the differences in sunlight were not significant, and the evaporation rate was considered to be about the same.

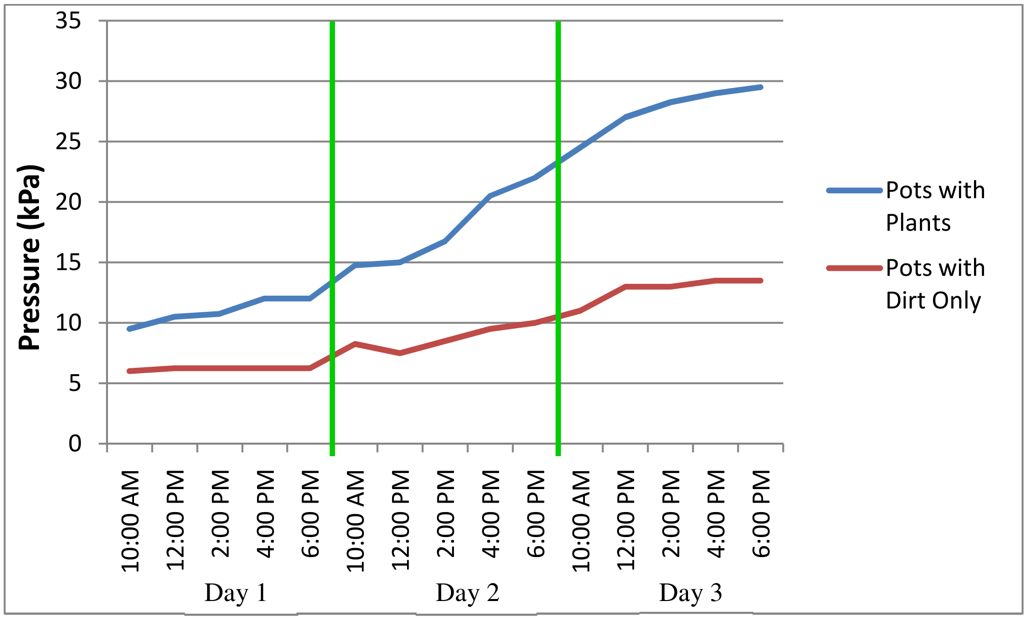


Figure 15: Pressure readings of Tensiometers increased as the soil dried after the rain.

The soil in the two pots with Golden Yarrows began to dry out more quickly because of the moisture that was absorbed by the plants. The blue line in Figure 15 is an average pressure reading for the two pots with plants, and the red line is an average reading for the pots without plants. The green lines separate the different days. There were small increases in the Tensiometer readings during the time between 6:00 p.m. and 10:00 a.m. the next morning. Plants generally do not transpire at night, but they may still be absorbing some water. Also, water would still evaporate from the surface of the soil during the night, and transpiration would continue while the sun was up, which would give a few hours after testing and before the first measurement was taken the next day.

As expected, an Anova analysis in Minitab showed that there was a significant difference in the Tensiometer readings depending on the day and depending on whether the pot had a plant in it or not (p value $< .001$). The number one signifies that there is a plant in the pot, and a zero signifies that the pot is filled with soil only (Figure 16). The average soil tension reading for the pots that had a plant was about 10 kPa higher over the three day period. The average pressure reading on day three was about 11 kPa higher than on day one. The main effect plot shows that clearly having a plant in the pot affects the wetness of the soil, and, not surprisingly, the longer the pots went without water the dryer the soil became.

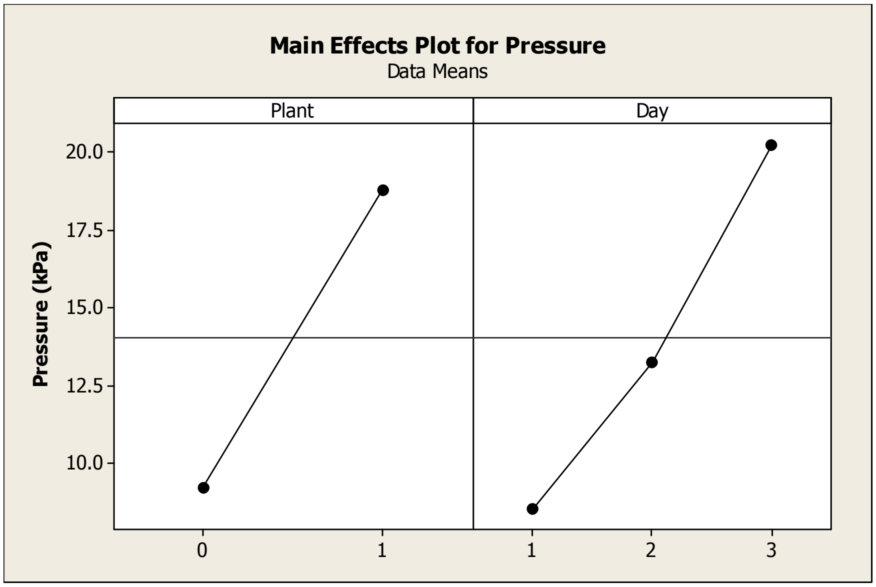


Figure 16: Main effects plot of day and plant on the pressure reading of the Tensiometers.

The two pots with plants were expected to get similar readings over the three days. Similarly, the two pots without any plants were expected to get similar readings from the Tensiometers. A box plot of the Tensiometer readings shows the effects of the day and whether there was a plant or not (Figure 17). The five readings taken each day every two hours starting at

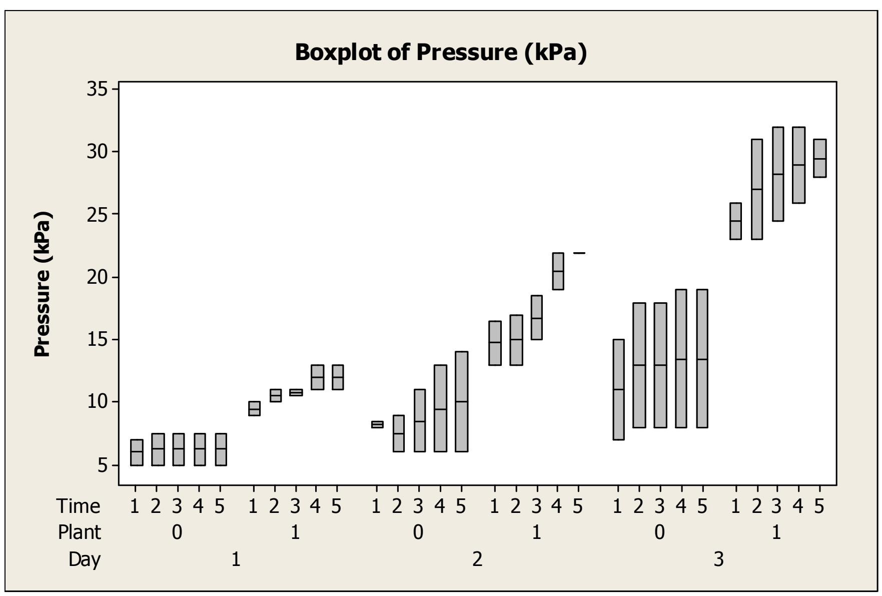


Figure 17: A box plot of the Tensiometer readings shows the variation in the readings.

10:00 a.m. and ending at 6:00 p.m. are signified by the numbers one through five. The pots with plants, signified again by a one, can be seen to be clearly higher than the pots without even though the range between the readings for any given time was as much as 10 kPa. The variation between the two pots without plants was consistently larger than the range between the two pots

with plants. The larger variation is believed to be a result of the soil conditions of one of the pots without a plant. This pot had readings that were close to the 0 kPa range for all three days, and the readings did not go up with the other three pots. One explanation for this phenomenon is that the Tensiometer in that in that pot could have been placed in an area surrounded by Super Soil which trapped moisture around the ceramic tip and caused the low reading.

One of the difficulties in this experiment was finding a way to have uniform soil. Originally, this experiment was attempted using Super Soil potting soil, which ensured that the soil was uniform throughout the four pots and would not impact the experiment. Also, the seedlings were grown in Super Soil by the nursery, so it made sense to keep all the soil consistent throughout the four pots. However, the Super Soil potting soil had likely been chemically coated to absorb water well because the Super Soil did not dry out even after weeks without water. Therefore, the Tensiometers continued to read 0 kPa because the soil remained saturated. The solution to this problem was to take dirt from the same area of a nearby field and transplant the plants into the new dirt. In order to transplant the Golden Yarrows, some of the Super Soil around the roots had to be moved with the plant so that they would survive. However, this also posed a problem because if the pots without plants only contained the dirt from the field, then the pots with plants would have a different composition of dirt around the plants. Therefore, a similar amount of Super Soil was placed in the middle center of each of the pots without a plant. The Tensiometer readings of one of the two pots without plants only increased about 3 kPa and were still only a few kPa away from the zero range that signifies that the soil is saturated with water.

Based on previous experiments in which the Super Soil retained water so well that the readings remained at 0 kPa for weeks, the likely explanation for one of the pots not drying out as the other pots did is that the Tensiometer in that pot was surrounded by Super Soil. If the ceramic tip was placed in an area that had only Super Soil in it, then the readings would remain near the 0 range because the Super Soil holds moisture better than natural soil. In order to improve this experiment for the future, the plants should be planted from seeds or very small seedlings and grown in the soil they will be tested in. Therefore, the problem of transplanting and keeping the soil consistent between the different pots will be avoided.

Conclusion and Recommendations

Ecosystems are interconnected webs of life, and human interaction with one aspect of an ecosystem can affect the ecosystem as a whole. However, in order to support the human population, we must be able to farm and get food and other resources from the environment. If we study the interactions of the ecosystem we can better understand how our actions might negatively impact an ecosystem and how damage can be prevented. In addition, we can study how ecosystems function without human intervention and use that knowledge to rebuild

ecosystems that have been damaged by past actions. There is undoubtedly room for improvement in the ways we utilize resources from the earth, and high-tech solutions can certainly play a role in increasing the efficiency of resource usage. However, we must not overlook the benefits of looking to the nature environment to provide us with solutions on how to utilize resources more efficiently, and how to repair any damage that we have done. Many communities, especially poor communities in the developing world, have problems associated with deforestation. Deforestation can have devastating consequences for the productiveness of the land and make farming and herding much more difficult.

In order to understand, the complicated interactions of an ecosystem, breaking down the different components and studying them one at a time can allow for an experiment with few enough factors to be implemented effectively. However, the complex interactions are difficult to study by looking at one piece at a time. If the resources are unavailable to conduct a large scale experiment with many different parts of an ecosystem present, then observational studies of existing ecosystems can provide useful information on the interactions taking place.

This project has focused mainly on the water absorption properties of plants; however, there are a number of other factors that must be studied in order to get the complete picture of an ecosystem. The effects of soil composition, nutrient intake and release by plants, and the interaction between organisms and plants are all topics for further research. In addition, this project has shown that soil Tensiometers can be used to study the water absorption properties of plants and contrast that to the environment if the plants weren't there; however, a longer scale experiment would provide more useful data. A more accurate picture of the effects of a plant on water absorption could be obtained if soil Tensiometers were used to test a plant over an entire season or over the lifetime of the plant.

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