ABSTRACT

Title of Document:	THE EFFECT OF WOOD BURIAL AND SUBMERSION ON DECOMPOSITION: IMPLICATIONS FOR REDUCING CARBON EMISSIONS
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Carbon cycles among soils, organisms, the atmosphere, water, and the Earth's crust. These fluxes make up a sizeable portion of the carbon cycle which holds potential for carbon sequestration. Team Carbon Sinks sought to sequester carbon in dead trees via burial and submersion. The team conducted a field experiment monitoring the decomposition of 125 wood samples. A lab experiment was completed to evaluate the variables that may affect decomposition in buried wood. Finally, a computer model was used to explore sequestration potential on a large scale. The field results showed that buried logs decomposed slower than exposed logs. The lab experiment suggested that wood should be buried as deep as possible, in a wet, cool area, and in

oligotrophic soil in order to inhibit decomposition. The model showed that decomposition could be effectively inhibited via burial, and could serve as an economically feasible way to decrease atmospheric carbon dioxide.

THE EFFECT OF WOOD BURIAL AND SUBMERSION ON DECOMPOSITION: IMPLICATIONS FOR REDUCING CARBON EMISSIONS

By

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Chapter 1: Introduction

1.1 Team Carbon Sinks

Team Carbon Sinks began in 2007 under the guidance of the University of Maryland Gemstone Program. The Gemstone Program encourages students to identify potential societal and scientific problems to research as an undergraduate thesis project. The program matches students who display similar interests for a proposed project to form multidisciplinary research teams where different backgrounds and skill sets can work toward a unified goal.

Team Carbon Sinks formed under a mutual concern for the environment and a common interest in testing new and innovative ways to tackle climate change issues. The team hoped both to develop a new perspective on the problem and to spur future research in the area. Under the guidance of Dr. Ning Zeng, University of Maryland Professor of Atmospheric and Oceanic Science, the team developed a research plan to study biological carbon sequestration, through field study, lab experimentation, and computer modeling. The field study was conducted in cooperation with the Wye Research and Education Center (WREC) in Queenstown, Maryland. WREC is a part of the University of Maryland College of Agriculture and Natural Resources (AGNR) and focuses primarily on agricultural research. On campus, AGNR also supported our lab experimentation through the Department of Environmental Science and Technology by providing experienced guidance for the methodology along with access to laboratory facilities and equipment.

As trees die and decompose, carbon dioxide (CO_2) is released into the atmosphere; Team Carbon Sinks sees a potential pool of carbon that can be captured from this process in the form of a carbon sink. The main goal of this thesis is to explore whether a method can be developed to store, via biological methods, the carbon that naturally exists in dead trees.

1.1.1 Research Questions

The overarching goal of this project is to determine how burying and submerging woody biomass affects its decomposition. The team explored different aspects of this question using a multi-faceted research design. In the field experiment, we sought to determine the effect of wood burial and submersion in a natural environment, specifically the effect of burial depth and soil composition on the decomposition of buried wood. In the laboratory, the main goal was to determine how several different variables affected decomposition. Finally, the modeling experiment aimed to investigate the long term effectiveness of wood burial as a form of carbon sequestration.

1.2 Background

1.2.1 Global Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC), the Earth's temperature has increased by 0.8^{o}C in the past century and is projected to rise anywhere between 2 and 8 ^{o}C by 2100 (IPCC, Working Group I, 2007). This relatively rapid increase in global temperature will significantly affect many living organisms on Earth. When the global temperature rises, permafrost and glaciers will melt, raising global sea levels. Even if sea levels only increase by one or two meters, huge tracts of land will be submerged, for example, highly populated areas including the Nile Delta, Southern Asia, Hong Kong, Shanghai, and many island countries

(IPCC, Working Group II, 2007; Junyong, 1997). Warming oceans will also directly affect marine biota. Increasing ocean temperatures have already resulted in coral reef loss by bleaching, which is caused by the corals overheating and expelling their symbiotic algae. Also, rising ocean temperatures reduce the level of dissolved oxygen. Less dissolved oxygen makes it harder for aerobic organisms to metabolize and function.

Through ice coring techniques, it has been discovered that the Earth's global temperature has varied throughout its history. In the past, the temperature changes were generally very gradual and populations of organisms usually had time to evolve or migrate. The problem with the present global climate change is the rate at which it is occurring. The IPCC suggests that the Earth is warming at this rate because of anthropogenic activities that release greenhouse gases into the atmosphere (IPCC, Working Group I, 2007).

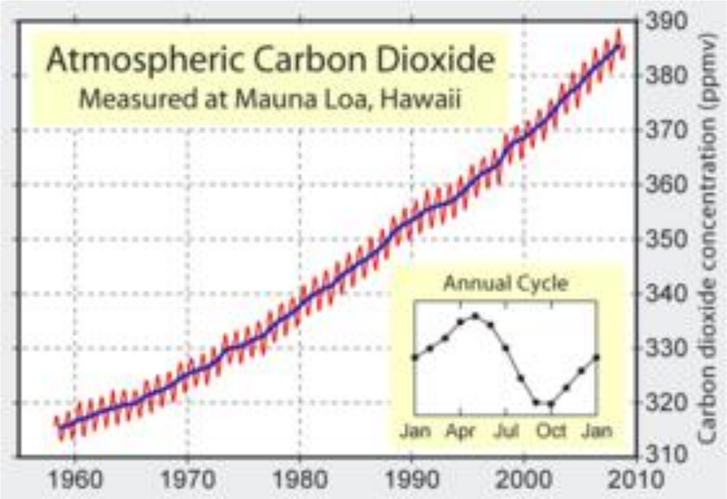


Figure 1: The Keeling curve – graphic representation of increasing atmospheric CO_2 concentration over time (Keeling, 1960)

As shown by the curve in Figure 1, there has been a measurable increase in atmospheric CO_2 since 1960 (Keeling, 1960). This increase can be attributed to the human addition of CO_2 to the atmosphere through a variety of sources, including fossil fuel burning and deforestation. Researchers attempting to address the problem of global warming have concentrated on reducing human emissions of CO_2. Additionally, other greenhouse gases, including methane and nitrous oxide, have shown significant increase over the past fifty years, however, the scope of this study only covers the role of CO_2 and potentially mitigating its negative effects.

1.2.2 The Carbon Cycle

Carbon cycles exist between organisms, the atmosphere, bodies of water, and the Earth's crust. Various elements of the environment interact with carbon in different ways; some may store carbon and some may release carbon, depending upon their individual properties. Carbon is stored in reservoirs, such as living organisms, soils, oceans, fossil fuels, and the atmosphere. Carbon flows between these reservoirs continuously due to both natural and anthropogenic processes, including photosynthesis, respiration, decomposition, and the combustion of fossil fuels. A reservoir that takes in more carbon from the atmosphere than it releases is known as a carbon sink. Conversely, a carbon source releases carbon into the atmosphere. Carbon flux into the atmosphere is the movement of carbon between a carbon sink or a carbon source and the atmosphere.

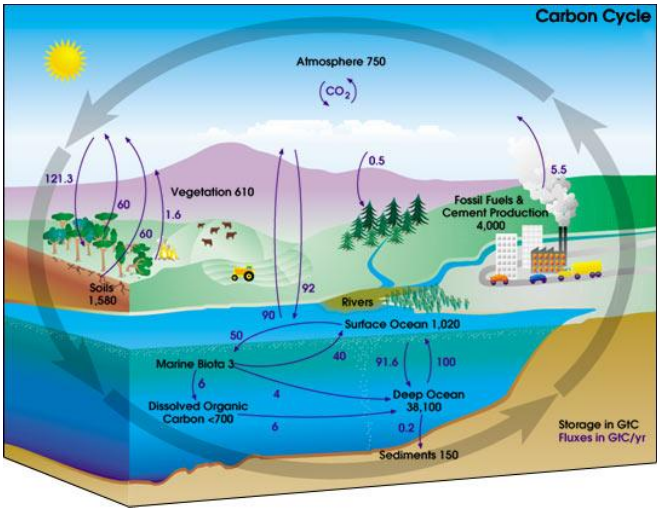


Figure 2: Diagram of the Earth's carbon cycle (NASA Earth Observatory, 2010)

There are several large naturally occurring carbon sinks, including oceans and forests. Despite the amount of CO_2 sequestered by these carbon sinks, there is still a net increase in the amount of CO_2 released into the atmosphere every year (Keeling, 1960). Current U.S. emissions from fossil fuel combustion are 1650 megatonnes of carbon per year (MtC y^{-1}) (Marland, Boden, & Andres, 2007), however U.S. forests only offset 10% of annual U.S. carbon emissions (Birdsey, Lucier, & Pregitzer, 2006).

Forests play a vital role in the carbon cycle and act as net carbon sinks, at least in the U.S. (Birdsey et al., 2006). Through photosynthesis, the process by which autotrophs (plants) take in sunlight, CO_2, and H_2O and produce glucose and O_2, globally, forests take in about 120 GtC y^{-1} from the atmosphere (NASA Earth Observatory, 2010). They also emit 60 GtC y^{-1}, globally, through respiration, the opposite reaction of photosynthesis in which glucose is broken down into CO_2 and H_2O (NASA Earth Observatory, 2010). The balance between photosynthesis and respiration yields a net capture of 60 GtC y^{-1} for forests. However, this does not take into account the amount of a forest's biomass that is made up of dead organic matter.

For example, in the U.S. 14% of a forest's biomass is in dead organic matter (Woodall, Rondeux, Verkerk, & Stahl, 2009). This detritus is broken down into its basic compounds by detritivores, which include bacteria and fungi, in a process called decomposition. Carbon, hydrogen, oxygen, and nitrogen, along with sulfur and phosphorous, make up the vast majority of all organic matter and are either incorporated into living organisms and soil or emitted as gas during decomposition. Globally, decomposition in forests accounts for most of the difference between photosynthesis and respiration, putting around 60 GtC y^{-1} back into the atmosphere (NASA Earth Observatory, 2010). This flux of carbon that occurs between forests and the atmosphere is responsible for a significant amount of the carbon that is released into the atmosphere each year.

1.3 Carbon Sequestration as a Way to Mitigate Carbon Emissions

Carbon sequestration has been proposed as a potential method for reducing the net amount of CO_2 released into the atmosphere each year (UNFCCC, 1998). These methods usually focus on either sequestering carbon in bodies of water or underground where it cannot readily escape back into the atmosphere (IPCC, Working Group III, 2007). Some researchers have proposed capturing the CO_2 released by power plants and pumping it into a geological storage site (IPCC, Working Group III, 2007). It has been estimated that power plants using available Carbon Capture and Storage (CCS) technology could reduce their CO_2 emissions by 80-90% (IPCC, Working Group III, 2007). The major problems with this strategy, however, are that CCS technology cannot be applied to automobile emissions, which comprise a significant portion of total anthropogenic carbon emissions, the technology itself is expensive, and the solution is not necessarily permanent.

Other methods have been proposed to sequester carbon in its solid state before it decomposes and is released into the atmosphere. One such method is the burial or submersion of agricultural residues (Metzger & Benford, 2001; Zeng, 2008). Residues (stalks, stems, etc.) that are not commercially sold make up over half of the biomass grown on farms. These agricultural residues contain large quantities of carbon, which, when left to decompose, release CO_2 and other greenhouse gases back into the atmosphere. It has been estimated that in the United States these agricultural residues account for 180 MtC y^{-1} (Metzger & Benford, 2001). It has been suggested that if these residues are buried or submerged, it may be possible to slow their decomposition and decrease the amount of CO_2 released into the atmosphere (Zeng, 2008).

Agricultural residues are not the only source of carbon that can be readily sequestered. Dead trees on forest floors, construction site wood wastes, and old furniture are just a few of the readily available sources of carbon that are thrown away, burned, or left to decay. Because decomposing dead trees on the forest floors account for a large carbon flux globally, sequestering a fraction of the dead wood by burial in the ground or submersion in water would prevent up to 10 GtC y^{-1} from being released back into the atmosphere (Zeng, 2008). Although only a percentage of the decomposing trees would be available for sequestration in practice, this could still be an important resource because 8.4 GtC y^{-1} is released due to fossil fuel emissions (Canadell et al., 2007). This means that sequestering only a portion of the wood on the forest floor would greatly offset the carbon emissions produced through the burning of fossil fuels.

Various studies support the proposition that the earth can retain carbon for long periods of time if it is buried underground. A study done at the Yale-Myers forest, which is located on the U.S. East Coast, showed that soils could store and retain more carbon when organic material was buried at depths of as little as 15 cm below the top of the soil compared to material lying on the surface (Kulmatiski et al., 2004). Furthermore, factors such as poor drainage of water through the soil and low pH in soil contributed to increased carbon storage (Kulmatiski et al., 2004).

1.4 Research Objective: Purpose and Significance

Although it is well known that forests can act as net carbon sinks, comparatively little research has been done on the decomposition rate of dead wood in varying environments and conditions, specifically with respect to underground and water burial (Kurz & Apps, 1999). There is also a general lack of literature on the quantity of dead wood on the forest floor, and this carbon reservoir is often neglected in carbon budgets (Zeng, 2008). Understanding the extent to which these conditions slow the release of carbon into the atmosphere provides a background for the creation of a carbon sequestration method.

Through an experimental determination of decomposition rates of wood under both soil and water as well as a comparative study of factors that influence decomposition, this project aims to identify whether burial or submersion significantly slow decomposition. If so, the project will also determine the most effective environment for sequestering carbon in forests. Through modeling and computer simulation the team intends to determine the potential for carbon storage if the sequestration technique is implemented on a large scale.

1.5 Study Approach

This study consists of two interrelated experiments, field research and a lab experiment, with the purpose of determining the different decomposition rates of wood under varying conditions.

In the field study, 125 small samples of loblolly pine were measured initially and then allocated to specific locations; 75 were buried underground at three predetermined depths determined to be within three different soil strata, 25 were left above ground as controls, and 25 submerged in a freshwater pond at WREC. Samples were removed and analyzed periodically over twenty months to determine the amount of decomposition, quantified by mass and volume changes, in each log and whether the different locations had a significant impact on the sample's rate of decomposition.

For the lab experiment, accelerated wood submersion systems were created to mimic the field research on a small scale by using sawdust, whose high surface area to mass ratio encourages decomposition, as the woody biomass in order to obtain measurable decomposition data in a short amount of time. Under this setup the impact of individual variables as well as the interaction of variables on decomposition could be tested in a controlled manner with rapid results. Decomposition was quantified in this experiment by measuring the amount of CO_2 released into the atmosphere. The results from the lab experiment provide additional insight into the field experiment, since the tested variables were also measured at the field site.

In order to explore the larger scale implications of the research, the decomposition rate of loblolly pine found for each field setting was then input into a computer modeling program. This program simulates the life cycle of a forest in order to determine the potential amount of carbon that can be sequestered after a prolonged period of time if the decomposition rate is slowed.

1.6 Hypothesis

Burying and submerging woody biomass will effectively deprive the biomass of sufficient oxygen for decomposition to occur. The deeper the wood is buried, the less oxygen will be present therefore the lowest burial horizon will return the slowest decomposition rate. Placing woody biomass in an anaerobic environment will significantly slow the decomposition and the release of CO_2 when compared to woody biomass left above ground.

Chapter 2: Literature Review

2.1 Human Influences on Climate Change

Climate change is the long term change in weather trends or patterns. While this process may occur over thousands or millions of years, there have been recent trends of much more rapid modern climate change. There are many important natural processes which have an impact on the global climate as well as anthropogenic sources which affect climatic patterns.

While this subject has been a source of great debate in recent years, there is a scientific consensus that human activity is very likely the cause of the rapid increase in global average temperatures over the past several decades. Recent reports from the IPCC (Working Group I, 2007) have concluded that:

1. "Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely (90%) due to the observed increase in anthropogenic greenhouse gas concentrations."
2. "From new estimates of the combined anthropogenic forcing due to greenhouse gases, aerosols, and land surface changes, it is extremely likely (95%) that human activities have exerted a substantial net warming influence on climate since 1750."
3. "It is virtually certain (99%) that anthropogenic aerosols produce a net negative radiative forcing (cooling influence) with a greater magnitude in the Northern Hemisphere than in the Southern Hemisphere."

Since the 1960s, researchers have paid increasing attention towards anthropogenic effects on climate change. This time frame is important for two reasons: human activity accelerated rapidly over this period and technology for observing the upper atmosphere became readily available. The general mechanisms for anthropogenic climate change are increasing atmospheric concentrations of greenhouse gases, global changes to land surface, and increasing atmospheric concentrations of aerosols.

2.1.1 Increased Greenhouse Gas Emissions

The greenhouse effect is a process by which an accumulation of atmospheric gases, or greenhouse gases, contributes to increasing surface radiative forcing. The mechanism for the increase in temperature results from solar radiation entering through the Earth's atmosphere. Once the solar rays are reflected by the Earth's surface, the accumulation of greenhouse gases prevents the solar radiation from escaping. Not only do the atmospheric gases heat up while absorbing increased radiation from the Earth's surface, but as the atmospheric gases emit radiation outwards, there is an increased amount of energy pointed at and absorbed by the Earth's surface. While CO_2 is not the most potent greenhouse gas on a molar basis, it has a large impact due to relatively high concentration of CO_2 in the atmosphere (with respect to other greenhouse gases) and the sheer magnitude of CO_2 released per year.

By burning fossil fuels, which releases copious amounts of CO_2, humans have impacted the composition of the Earth's atmosphere. The burning of fossil fuels accounts for about 75% of the anthropogenic emissions of CO_2 (IPCC, Working Group I, 2007). This has led to an increase in the atmospheric concentration of CO_2 and therefore has increased the atmosphere's capacity for slowing the release of infrared radiation back to space.

Not only have humans led to an increase in atmospheric CO_2, but anthropogenic impacts have been felt by releasing inordinate amounts of methane, chlorofluorocarbons (CFCs), and nitrous oxide all of which are much more potent than CO_2. These gases also contribute to the formation of tropospheric ozone. Since the industrial revolution of the mid-eighteenth century, CO_2 and methane have increased 36% and 148% respectively (EPA, 2008). Through analysis of ice core data that spans 650,000 years, researchers have shown that these levels are much higher than any previous levels in human history (Petit et al,, 1999; Siegenthaler et al., 2005; Spahni et. al, 2005).

2.1.2 Land Use Changes

Since humans began to modify the natural environment into built environments, sweeping changes in global land use have occurred. Not only has the impact of urbanization been felt throughout some developed nations by the processes of urban sprawl and habitat fragmentation, but larger changes such as global deforestation and desertification have become increasingly dramatic.

Cutting forests in temperate ecosystems, where they are a main carbon sink, is a prevailing, yet potentially hazardous, modern trend. Forests have become increasingly sparse over the last century and deforestation is becoming a global phenomenon. This has occurred as humans have spread out over time and utilized forests as a commodity or cleared land for agricultural or residential use. As trees grow, they collect and store a large amount of carbon which is later released into the atmosphere via burning or decay (Fearnside & Laurance, 2004).

Since there have been high rates of deforestation with smaller rates of reforestation, a great deal of habitat and biodiversity have been lost over the past 100 years. While the exact quantitative impact of deforestation on global climate change is debated, some experts recently estimated that deforestation accounts for about 12% of anthropogenic CO_2 release (van der Werf et al., 2009).

2.1.3 Increased Aerosol Concentrations

The release of pollutants, as well as aerosols, from volcanoes has had a similar impact in terms of the process of global dimming. Global dimming is a reduction of solar radiation received at the Earth's surface due to the reflection of incoming rays from atmospheric particles. The process of global dimming has been argued to have partially counteracted anthropogenic global warming (Mitchell et al., 2001). Some atmospheric pollutants scatter and absorb incoming solar radiation, thus preventing sunlight from reaching the surface. In addition, some soot and aerosols act as small cloud particles which increase the reflectivity of clouds (Twomey, 1977).

2.2 Carbon Sequestration

Carbon sequestration is the term applied to any method of storing either carbon or CO_2 over a long period of time. There is a net reduction of the amount of CO_2 that enters the atmosphere, either from anthropogenic or natural sources. Numerous techniques have been proposed to sequester carbon.

2.2.1 Efficacy of Carbon Sequestration

Many approaches to mitigating climate change require people to make a significant lifestyle change. For example, people are typically encouraged to drive fuel efficient vehicles and consume less power. If CO_2 were to be sealed in such a way that it cannot re-enter the atmosphere, this would have a subtractive effect on the increasing carbon emission trends. Therefore, carbon sequestration would allow for anthropogenic CO_2 emissions to have a smaller impact on global climate. The practical application and individual effectiveness of various carbon sequestration techniques will be discussed below.

2.2.2 Carbon Sequestration Methods

Numerous methods of sequestering carbon have been proposed. These methods can be divided into loose categories, consisting of biological, physical, and chemical methods. Biological methods directly manipulate organisms to sequester carbon. Physical methods may use a biological source of carbon, but the actual sequestration is performed by placing the carbon in an environment from which it cannot escape into the atmosphere. Chemical methods use a variety of specific chemical reactions to either capture, or prepare a medium to capture, CO_2.

2.2.2.1 Biological Methods

The following methods provide an overview of the research in biological carbon sequestration. Biological sequestration methods augment natural processes to improve their sequestration capacity. By definition, this must alter natural equilibriums, and any unregulated biological method has the potential to harm the environment.

2.2.2.1.1 Ocean Fertilization

Ocean fertilization is the addition of a specific nutrient, usually iron or nitrogen, to induce phytoplankton growth. When one nutrient can be determined to be the limiting factor for phytoplankton growth in otherwise nutrient-rich water, the addition of that nutrient can cause a large plankton growth known as a bloom. Photosynthetic organisms chemically utilize light from the sun and absorb H_2O and

CO_2 in order to create food and release O_2. Since phytoplankton photosynthesize, this bloom also leads to increased absorption of CO_2.

Research conducted since the early 1990's has shown that ocean iron fertilization can lead to the growth of plankton blooms. In areas of ocean all over the world, researchers have found areas of ocean with high nutrient concentrations, but low chlorophyll concentrations (Boyd, 2007). This means that despite a readily available supply of nutrients, phytoplankton did not grow well in these sections of ocean. After initial small-scale experiments, deposits of iron ranging from 300 kg to more than 2800 kg of iron were added directly to ocean water. These studies found that addition of iron did cause the production of plankton blooms in these nutrient rich, chlorophyll poor areas of the ocean. Through these experiments, it has been shown that one third of the ocean has a nutrient profile in which iron is the limiting nutrient (Boyd, 2007). This type of sequestration would allow for much of the ocean to be used as a carbon sink. On a short term scale, this method has been proven, and now needs long-term experimentation to yield more concrete answers as to its use for carbon sequestration (Boyd et al., 2007).

Much like ocean iron fertilization, urea fertilization would raise levels of a limiting nutrient in an attempt to stimulate phytoplankton growth. Karl and Letelier (2007) state that almost 80% of the world’s oceans have a low nitrate concentration. In these areas, nitrate seeding could lead to an increase in phytoplankton blooms. The primary aim of Karl and Letelier's paper was to address the use of the oceans as carbon sinks, and much of the initial research into this method has been completed.

An issue shared by both types of fertilization discussed above is the possible ecological impact of adding nutrients to the ocean. Urea fertilization was acknowledged to be a possible ecological hazard (Karl & Letelier, 2008). In the iron fertilization experiments, the consequences of extended iron seeding were not considered, because the researchers were not explicitly concerned with iron fertilization as a method of carbon sequestration (Buessler et. al, 2008). Not only could iron fertilization be ecologically hazardous, but its efficacy in carbon sequestration will take years to assess.

2.2.2.1.2 Ocean Mixing

Ocean mixing relies on the same concepts as fertilization – if a nutrient poor area of the ocean is supplied with nutrients, phytoplankton will flourish and photosynthesize. In the case of ocean mixing, this is done not by nutrient seeding, but by circulating nutrient-rich water from 100 to 1000 meters below the surface using pipes (Karl & Letelier, 2007; Lovelock and Rapley, 2007). The circulation pipes could be powered by wave action, and allow the nutrient rich water to cycle to the surface, where it could nourish phytoplankton.

The possible consequences for this are much like those for ocean fertilization. The flux of nutrients from deeper in the ocean to shallow waters could have unintended ecological effects on both the surface and deeper waters. Ocean mixing could result in a fundamental change in habitat types in the ocean. As Lovelock and Rapley (2007) acknowledge, it is possible that wave action will not be enough to generate the suction in the pipes, or that functional pipes could upset the chemical balance in the ocean.

2.2.2.2 Physical Methods: Carbon Capture and Storage

Physical carbon sequestration methods trap CO_2 as non-organic carbon, and trap this carbon in physical formations. These methods typically fall under the broad umbrella of Carbon Capture and Storage.

Carbon Capture and Storage (CCS) is one of the foremost efforts in carbon sequestration research. In this form of carbon sequestration, carbon is removed from industrial emissions and sequestered. Many methods have been proposed to do this, several of which are far along in implementation studies (IPCC, 2005). These methods can be defined loosely based on how they seek to capture carbon and how they will sequester it once it is captured. Carbon can be removed from emissions either before or after combustion, or the gas in which a fuel is combusted can be manipulated to produce a nearly pure CO_2 waste gas (IPCC, 2005). Once captured, the CO_2 can either be stored geologically or by injection into the ocean (IPCC, 2005). CCS is a very broad umbrella in which several other methods of carbon sequestration are used to sequester carbon. There are attempts to increase CO_2 capture in power plants, one of the largest emitters of carbon, via methods like the chemical schemes discussed below.

2.2.2.3 Chemical Methods

In chemical methods of sequestration, chemical reactions are used to augment natural CO_2 collection processes and then store the CO_2 where it is made.

2.3.2.3.1 Mineral Sequestration

In the environment, CO_2 reacts naturally with calcium or magnesium oxides to form carbonates by the reactions:

$$CO_2(g) + CaO(s) \rightarrow CaCO_3(s)$$

$$CO_2(g) + MgO(s) \rightarrow MgCO_3(s)$$

This reaction is exothermic, and proceeds spontaneously under normal environmental conditions (Goldberg, Zhong-Ying, O'Connor, Walters, & Ziock, 2001). Although the reaction is spontaneous, at standard conditions it is also very slow (Goldberg et al., 2001). Several methods have been devised to increase the rate of CO_2 absorption, culminating in a process that could be used to absorb CO_2 on an industrial scale (Goldberg et al., 2001; Zhong-Ying, O'Connor, & Gerdemann, 2006).

2.2.2.3.2 Ocean Acid Neutralization

CO_2 can shift from the gaseous to the aqueous phase by the following reaction:

$$CO_2\ (g) + H_2O\ (l) + CO_3^{2-}\ (aq) \rightarrow\ 2HCO_3\text{-}\ (aq)$$

The equilibrium point of this reaction is determined by the pH of the water, the concentration of CO_3^{2-} and partial pressure of CO_2. As the concentration of CO_3^{2-} and the partial pressure of CO_2 increase, the ability of water to absorb CO_2 increases. This reaction produces an acid, so an increase in pH leads to increased dissolution of CO_2.

2.2.3 Carbon Sequestration through Forest Management

Not only do the world's forests play a key role in the global carbon cycle, but in doing so, they have an estimated uptake of 3.3 GtC y^{-1} (IPCC, Working Group I, 2007). As forests cover about 30% of the Earth's surface, there is a vast opportunity for global bioremediation. In the Fourth Assessment Report of the IPCC, it was estimated that the forested areas of the world held a vast biophysical mitigation potential of around 5.4 GtC y^{-1}. In an attempt to maximize CO_2 uptake by forests and therefore increase biophysical mitigation, many forest management strategies may be employed. One such strategy involves reducing emissions from deforestation and forest degradation by taking better care of the forests and ensuring they are healthy; by releasing less CO_2 while maintaining high levels of uptake, there is a net increase in CO_2 absorption by forests. Lower CO_2 emission levels and net increases in absorption by forests can be accomplished through reduction of decomposition and proper maintenance of growing stands. Another strategy revolves around enhancing the sequestration rate in existing and new forests, which also increases the net CO_2 uptake of forests. This is accomplished through forestry practices such as maximization of water, sunlight and nutrients.

Conceptually, the terrestrial carbon cycle in forests occurs in two phases: a long, slow uptake of carbon followed by short, rapid rates of carbon release through fire or harvest (Masera et al., 2003). Forests are generally visualized using an estimation of individual stands. The net uptake of that forest is calculated by summing the net CO_2 absorption of each stand in a forest. While each stand may act as either a carbon sink or a carbon source, forests are made up of a great diversity of stands in many different stages of development. While a stand in old-growth state is the largest net carbon sink, if harvesting was halted entirely in order to maximize CO_2 uptake, societal needs for timber would not be met. This would result in higher greenhouse gas emissions as more higher-energy materials would be produced and, relatively, more fossil fuels would be burned (IPCC, Working Group II, 2007). This demonstrates that there must be a balance between maximizing carbon reuptake in forests and societal needs that demand deforestation.

2.2.3.1 Wood Decomposition

Wood decomposition occurs by several pathways. When in an aerobic environment, wood is primarily decomposed by fungi. In an anaerobic environment, such as that found in this study, wood is instead decomposed by bacteria (Hedges, Cowie, Ertel, Barbour, & Hatcher, 1985). The length of time it takes for wood to decompose is also variable, and can be affected by temperature, moisture, tree species, and the type of organism decomposing the wood, among other factors (Hedges et al., 1985; Jurgenson et al., 2004).

2.2.3.1.1 Aerobic Decomposition

Decomposition of wood in the presence of oxygen is carried out mainly by fungi, which are obligate aerobes (Hedges et al., 1985). This is due to the higher rate at which fungi can digest wood compared to bacteria. There are two main types of fungi which degrade wood: brown-rot and white-rot fungi. Brown-rot fungi selectively degrade cellulose and hemicellulose, while white-rot fungi preferentially degrade lignin (Blanchette, 1984; Flournoy, Kirk, & Highley, 1991). This allows for the whole of the tree to be degraded by fungi. Fungi, under natural conditions, degrade cellulose faster than lignin (Jurgensen et al., 2004).

The time it takes for wood to decay varies greatly between tree species and even between the same species found in different sites. A study of coarse woody debris in Russian forests found decomposition rates ranging from 1.5% to 7.8% per year, with variation of as much as 3.6% per year within one species (Yaskov, Harmon, & Krankina, 2003).

2.2.3.1.2 Anaerobic Decomposition

Wood interred underground is decomposed by anaerobes. As mentioned above, fungi are obligate aerobes, and so cannot degrade wood that has been buried. Instead, the primary decomposers will be bacteria (Hedges et al., 1985). Various anaerobic bacteria are capable of decomposing the components of wood, like fungi, cellulose and hemicellulose are degraded at a higher rate than lignin (Hedges et al., 1985). When wood is decomposed by anaerobic bacteria, methane gas is evolved (Chynoweth, 1996).

2.2.3.1.3 Decomposition Timeline

The rate at which dead wood decomposes is variable, and contingent on numerous factors (Jurgenson et al., 2004). The Jurgenson study found decay rates between 1% and 8% per year for woody debris on the forest floor. A study of buried wood found a deposit of approximately 2500-year-old spruce, which had little to no decay, within six meters of a similarly aged deposit of alder wood that had decayed significantly (Hedges et al., 1985). This variability shows that there is a possibility of controlling decay by carefully manipulating what type of wood is buried, and in what conditions the wood is buried.

2.2.3.2 Maximizing Forest Carbon Uptake

The IPCC Fourth Assessment Report summarized and categorized different options for maximizing net forest carbon uptake: “reduction of deforestation, as well as afforestation/reforestation,…increasing the stand-level carbon density…increasing the landscape-level carbon…and substituting forest-derived biomass for high-energy materials and fossil fuels” (IPCC, Working Group III, 2007).

2.2.3.2.1 Deforestation/Afforestation

Reducing deforestation globally is the mitigation technique that would have the largest and most rapid impact on short term carbon stocks. Deforestation releases about 350-900 tonnes of CO_2 per hectare (IPCC, Working Group III, 2007). The large range is based on variability in the cause of deforestation as well as the alternative land-uses of each hectare. Afforestation also has a highly variable impact on carbon stocks, ranging from 1 to 35 tonnes of CO_2 per hectare per year. This variability is based on the tree species as well as the site. While these techniques require a large initial investment of time, energy and money, the returns in the long-term cover the initial costs (IPCC, Working Group III, 2007). While there is a possible delay of multiple decades before the new forest can be cultivated for economic purposes, the afforested area can prevent erosion as well as other non-carbon oriented benefits that can, in some situations "more than off-set afforestation costs" (Richards & Stokes, 2004). This is, of course, based on market prices for the environmental services being provided and the value to the landowners.

2.2.3.2.2 Increasing Carbon Density

There are many methods aimed at increasing the carbon density of a forest at the stand level and the landscape level. At the stand-level, strategies such as promoting forest cover, minimizing loss of dead organic matter to the atmosphere, and avoiding slash burning and other activities that result in high levels of emissions will result in an increased carbon density per meter. One simple strategy to increase stand density includes planting trees after anthropogenic or natural disturbances, which will result in accelerated tree growth and will reduce the net losses of carbon. Since landscape-level forest carbon accumulation is determined by the sum of the stands, implementation of stand-level techniques on a large scale will undoubtedly have impacts on the landscape level. In addition to the stand-level techniques, an increase in harvest rotation length will generally increase carbon pools with some exceptions (IPCC, Working Group III, 2007).

2.2.3.2.3 Substitution of Wood Products for High-Energy Materials

By increasing off-site carbon stocks, that is, by removing wood from forests and storing those materials elsewhere, the issue of stand saturation is addressed. As long as the harvest size is less than the amount of growth of a forest, wood products can be created and address the needs of society, like timber and energy, while allowing forest carbon stocks to increase. The duration of carbon storage varies based on how the woody materials are used, from days for biofuels, to many decades for houses or furniture (IPCC, Working Group II, 2007). Using wood products instead of concrete, steel, aluminum and plastics can result in significantly lower emission rates (Petersen & Solberg, 2002).

2.2.4 Environmental Hazards

There are ecological risks associated with any activity that alters the environment. The wood burial sequestration method relies, at least partly, on the removal of wood from a natural forest ecosystem. The wood also may decompose via anaerobic processes once it is interred underground, resulting in increased methane emissions.

2.2.4.1 Wood Removal

Woody biomass, whether standing or down on the forest floor, serves as an important part of a forest's ecosystem. Standing trees prevent soil erosion and provide habitat, while downed trees play a key role in biodiversity, habitat, and nutrient cycling (Janowiak & Webster, 2010). This does not mean that woody biomass cannot be removed from a forest in a sustainable and responsible manner. As long as they are removed without overly disturbing the soil, live and dead standing trees can be removed from a forest without a large impact on the forest's productivity (Janowiak & Webster, 2010). By following strict guidelines and coupling the wood burial method to existing forest management policies, it is possible to collect wood without harming the environment.

2.2.4.2 Methane

Methane is a potent greenhouse gas, with a global warming potential 21 times greater than CO_2 (Chynoweth, 1996). Methane is released when wood is decomposed under strict anaerobic conditions (Chynoweth, 1996). Internment of wood underground places it in anaerobic conditions, causing at least some decay to result in methane production. If greater than 5% of the carbon in the tree is converted to methane and released to the atmosphere, this results in a net increase in greenhouse gas from wood burial. A study of wood deposited in a landfill 46 years earlier showed that around 18% of the carbon in the wood had decayed (Ximenes, Gardner, & Crowie, 2008). This implies that if 30% of carbon decomposition in buried wood results in methane release, then wood burial will have increased global warming after 50 years.

One possible solution to this problem comes from currently available landfill technology. Some developed landfills have wells or taps which collect methane from inside the landfill and burn it as a power source (Bogner, Meadows, & Czepiel, 2007). This approach could be applied to a wood internment site, which would allow the conversion of methane to CO_2, mitigating any increase in the global warming potential of the buried wood.

2.3 Carbon Economy

The Kyoto Protocol was an agreement made in Kyoto, Japan in 1997, that stated any nation who signed it would “cut their greenhouse gas emissions to 5.2% of 1990 levels by 2012” (UNFCCC, 1998). The Kyoto Protocol is the impetus for the introduction of carbon markets in numerous countries.

Carbon markets are a method for controlling carbon emissions. The general concept is as follows: first governments set a limit, or cap, on overall emissions for greenhouse gases. The allowed emissions are usually measured in mass of CO_2 equivalent, based on the emissions of a number of greenhouse gases and their respective global warming potential relative to CO_2. Next, the allowed emissions are divided amongst “all the major emitters in the economy so that each industry sector, and then each [carbon emitter] within each sector, knows how many tonnes it can emit each year” (Hamilton, 2009). These amounts are issued in units called permits, or allowances. Each permit is equal to one tonne of CO_2 equivalent. This allows for the trading of emission permits to other firms or industries that cannot complete the year within the allowed amount of emissions. Thus carbon gains a value from market trading. This gives firms and industries flexibility: they can either reduce emissions or pay to acquire more permits. Additionally, this provides incentive for firms to come in under their carbon budget. If they have remaining permits they can sell them for the carbon allowance market value. This system “ensures that the overall national target for reducing emissions is met because there are only a finite and limited number of permits on issue” (Hamilton, 2009).

To increase the flexibility of the system, most carbon trading systems also offer a second type of carbon financial instrument. These are called offsets, or carbon credits. In addition to buying permits other firms do not need, firms can also pay another firm or organization to cut its emissions, instead. These credits then can be used to allow the purchasing company to emit more CO_2. The general concept is that saved carbon anywhere is beneficial since the global economy is operating on one planet. However, firms cannot pay to have all their emissions offset without working to reduce them. Offsets are usually limited to a proportion of overall emissions.

Two of the currently existing carbon trading systems are the EU Emissions Trading Scheme (EU ETS) and the Regional Greenhouse Gas Initiative (RGGI). Though the EU ETS has not been overtly successful as of yet because in its trial phase permit allocations were not tight enough, it is expected to have more positive results after its next phase. However, in 2007, “a group of environmental economists published an independent study of the EU ETS in the Review of Environmental Economics and Policy, concluding that the scheme was reducing emissions and was ‘by far the most significant accomplishment in climate policy to date’ worldwide” (Hamilton, 2009). “RGGI is the first mandatory, market-based effort in the United States to reduce greenhouse gas emissions. Ten Northeastern and Mid-Atlantic states have capped and will reduce CO_2 emissions from the power sector by 10% by 2018” (RGGI, 2010).

Should wood burial prove to be a successful carbon sequestration method, it could be used as a carbon offset. This would give it an economic value anywhere a carbon market was in place. We hope that through this and future research, carbon sequestration by wood burial will become an approved carbon offset method used in the global carbon market.

Chapter 3: Field Experiment

3.1 Experimental Design

3.1.1 Overview

The goal of this experiment was to evaluate the varying rates of decomposition of dead wood buried at four different depths and submerged in water over a twenty month time span. Measuring the decomposition of the wood disks over time reflects the amount of carbon that has or has not been released back into the atmosphere. This experiment tested the hypothesis that a piece of dead wood buried underground or underwater will decay more slowly, thus releasing less carbon in a given period of time than a piece of dead wood decomposing on the surface. Decomposition results of the five different situations were compared to draw conclusions about the potential to sequester carbon in such a manner.

3.1.2 Site Selection and Characteristics

3.1.2.1 Benefits of WREC

The experiment was conducted at WREC in Queenstown, Maryland. At this site, a small grassy patch of land, shown below in Figure 3, and a nearby pond, shown in Figure 4, were used for this experiment. Throughout the duration of the experiment, the land used for burial was not mowed, and thus the area became slightly overgrown with grasses.

The land at WREC was chosen for several reasons. First, since this land was previously used as farmland, the soil is representative of much of the farmland in the southeastern United States (McDaniel, 2007). Soil that has been used for farmland is likely to have been treated with fertilizer and therefore has increased levels of nitrogen and other nutrients that may increase decomposition rates. The soil used for farmland is generally homogeneous which means that a soil sample from one area of land can be used to represent the entire experimental area.

Figure 3: Field site at WREC

Figure 4: Pond at WREC

Other benefits of WREC include its proximity to the University of Maryland at College Park and the willingness of the staff to aid in the team's experiment. Everything needed for the experiment was on site at WREC and at the team's disposal. We were provided with all the tools needed, both for digging and for measuring, as well as ovens for drying the disks. Additionally, at WREC, the temperature and pH of the pond were recorded regularly, and a recommendation for a soil analysis company they work with was provided.

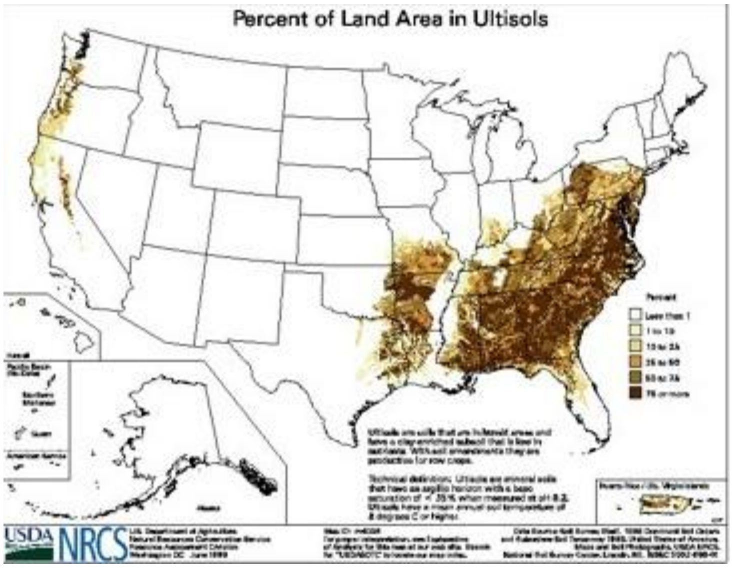


Figure 5: Ultisols in the United States

“The 'red clay' soils of the southeastern United States are examples of Ultisols. They are the dominant soils of much of the southeastern United States. Because of the favorable climate regions in which they are typically found, Ultisols often support productive forests (McDaniel, 2007). This soil's high forest productivity and high acidity make it a promising soil type for our experiments. The relatively fast growth of trees combined with a slow decomposition rate in the soil may mean that trees can be buried for a long time in the forests in which they grew.

3.1.2.2 Soil Horizons

The term 'horizon' is used to describe distinct layers, or strata, that occur naturally in soil. Soil horizons occur due to the actions of percolating water as well as the influence of biological agents. At WREC, the team used a coring tool to determine the nature of the horizons present in the field and discovered three distinct strata. The team aimed to evaluate how the varying depths and compositions of soil could affect the decomposition of a log and decided to use the deepest point of each horizon for the placement of the wood samples. We used the deepest point in each horizon to keep a uniform depth among all samples in each horizon and to ensure the sample in the A horizon did not become exposed due to weather. The four different soil horizons are described in more detail below.

The surface horizon of the soil is a thin layer of slightly decomposed organic litter; this is known as the 'O' horizon, or the humus. This horizon is often made up of leaves, needles, lichens, twigs, moss, and other organic debris in varying states of decomposition. The humus is never saturated with water for long periods of time, and the mineral fraction of the material is only a small percentage of its volume.

Below the humus is the 'A' horizon, which is found 5 to 15 centimeters deep on the site. This horizon is often the darkest in color because it contains the most organic material such as plant and animal remains. The 'A' horizon experiences more biological activity than any of the other horizons due to the higher concentration of insects, fungi, and bacteria. All or much of the original rock structure has been obliterated in this horizon.

The 'B' horizon is below the 'A' horizon and shares the characteristic of having total or nearly complete obliteration of the rock structure. It is located from about 15 to 50 centimeters below the surface. This layer is often reddish or brown in color due to its clay composition and iron oxide that is washed down from the above horizons. A majority of the 'B' horizon is made up of illuviated material, or material that has washed down from other horizons, and is therefore often called the 'zone of accumulation.'

The 'C' horizon is characterized by having fewer biological organisms than the other layers and very little organic matter, except where roots have penetrated. This layer is not affected by weathering, soil forming processes, and therefore contains chunks of bedrock, coral, and shells. The soil fragments in this layer are less fine than in the above layers due to less pedological development giving it a sandy texture. The 'C' horizon starts approximately 50 centimeters below the surface and ends around 120 centimeters.

3.1.3 Variables of Interest in Soil and Pond Water Composition

Specific soil factors affect the rate at which the buried wood decomposes; similarly, water chemistry factors affect the decomposition rate of the submerged wood. Samples of the soil horizons and pond water were taken periodically in order to determine which field environment is best suited for slowing decomposition for the purpose of sequestering carbon. The soil samples were analyzed for nutrients that play a significant role in fertilization and organic development because fostering this development would also encourage the growth of organisms that play a role in decomposition (Espinoza, Slaton, & Mozaffari, 2008). The significance of each nutrient, according to A&L Eastern Laboratories where the soil was analyzed, is detailed in the sections below ("Elements of Garden Fertilizers", 2006).

3.1.3.1 Nitrogen and Carbon

The levels of nitrogen and carbon in the soil indicate rates of soil respiration and the ratio of nitrogen to carbon indicates certain soil interactions (Hobbie, 2008).

Also, nitrogen is a main component of amino acids and proteins necessary for plant growth, therefore nitrogen deficiencies limit this growth ("Elements of Garden Fertilizers", 2006). Nitrogen and carbon dioxide levels in the water indicate the point in the water cycle and the presence of certain bacteria.

3.1.3.2 Phosphorus

The presence of phosphorous is necessary for respiration and photosynthesis to occur, playing a particular role in plant rooting; deficiencies often stunt plant growth. High levels of phosphorous can stimulate certain biochemical pathways, thus affecting decomposition (Laiho & Prescott, 1999).

Phosphorous is a main chemical ion in fertilizer, therefore the measured quantity of soil could indicate whether the soil has had fertilizer added. Areas with a combination of clay soils and high rainfall often have low levels of phosphorous, and the chemical also can react with other soil chemicals, depending on soil pH, to make the nutrient insoluble to plants ("Elements of Garden Fertilizers", 2006).

3.1.3.3 Potassium

According to A&L Eastern Laboratories, plants require sufficient potassium levels in order to perform vital cellular processes and a deficiency leaves the plants more susceptible to disease.

3.1.3.4 Magnesium

Magnesium is a vital component of chlorophyll and required for photosynthesis to occur; a lack of the nutrient causes leaves to yellow and ultimately die. There is also a relationship between magnesium absorption and soil pH; neutral soil enhances plant uptake.

3.1.3.5 Calcium

This nutrient plays a role in plant cell division and growth; sufficient water is necessary, however, for the nutrient to travel through the plant. The interactions of soil chemistry have a significant impact on calcium absorption; high levels of potassium or nitrogen can lead to a water shortage and impede the effectiveness of calcium, and calcium deficiency is also often linked with low soil pH ("Elements of Garden Fertilizers", 2006).

3.1.3.6 Soil and Water Temperature

Soil or water temperature determines what organisms may live in the soil and is also an indicator of soil respiration rates (Wells, 1995).

3.1.3.7 Soil pH (Land Only)

The water content and pH of the soil gives clues as to which organisms may be living in the soil (Wells, 1995). There are also many correlations between pH and a plant's ability to up take various soil nutrients.

3.1.3.8 Salinity and pH (Pond Only)

Throughout the field experiment, the salinity and pH of the pond were measured regularly. These factors are indicative of the organisms that may live within the pond (Gulis, Rosemond, Suberkropp, Weyers, & Benstead, 2004). The presence of organisms is significant because different organisms may encourage decomposition in the wood samples despite the generally anaerobic nature of water submersion.

3.1.4 Wood Selection

3.1.4.1 Loblolly Pine Overview

The loblolly pine (*Pinus taeda*) is an appropriate tree in any study that is designed to be broadly applicable for a number of reasons: its huge range in the United States, including the mid-Atlantic region; its importance as a timber species, especially in the southern U.S.; and the relatively low density of the species (Sandström, Petersson, Kruys, & Stahl, 2007). We cut a 10 meter loblolly log into samples for our experiment.

3.1.4.2 Geographic Range

As can be seen in Figure 6, the native range of the loblolly pine blankets the southeastern United States, from western Texas east to the Atlantic, and north along the coast through North Carolina, Virginia, eastern Maryland and Delaware, ending in southern New Jersey.

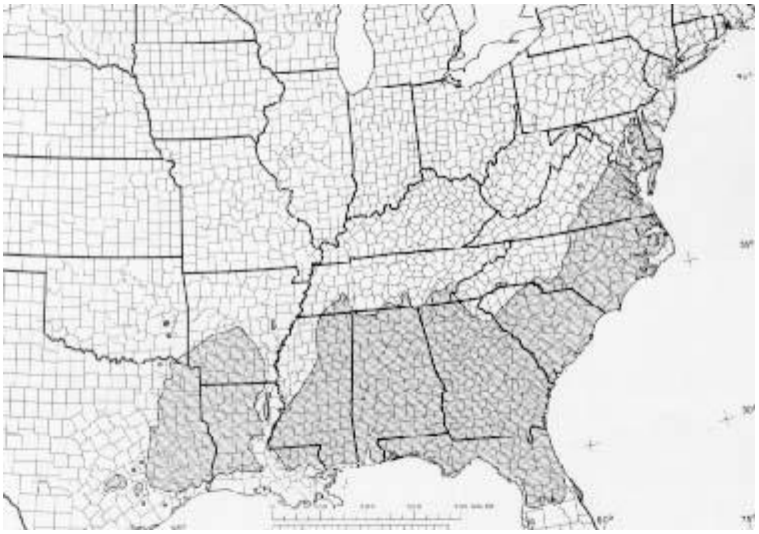


Figure 6: Native range of *Pinus taeda*

3.2 Field Experiment Methods

3.2.1 Pre-burial Methods

3.2.1.1 Method for Labeling Samples

To ensure that the condition of each disk could be compared pre- and post-burial, each sample was labeled individually. Each disk had an identifier that contained both a number and a letter. The letters A through Y corresponded to the column in which the disk was buried. All disks with the letter Z were submerged in the pond. The number on the disk ranged from 1 to 126 and was unique to the disk. The number represented the position of the disk in the soil column. This system made it easy to identify what burial depth the specific sample was from. For instance, sample A1 was the surface sample of column A, while A4 was the deepest sample from column A.

Two methods were used to attach the identification number to the disk. First, the number was written on both faces of the sample with a permanent marker. The number was also written on a small square piece of transparency paper and attached to the sample with a stapler. The redundancy of the labeling ensured that each sample was identified correctly post-burial and that the data was accurately collected and recorded.

3.2.1.2 Method for Taking Volume Measurements

The literature and past studies involving the decay of woody pieces indicate that there are two distinct methods that have been proven to successfully measure the volume of the logs and their pieces of bark. These two methods specifically are water displacement and a dimensional analysis which includes measuring the cross sectional area and multiplying it by the width of the sample to achieve the volume

(Barker, 2008; Sandstrom et al., 2007). The team chose to use a standard water displacement methodology for volume measurement given the equipment that was readily available when taking measurements at WREC. In addition, the odd shape of the samples used would have made measuring the cross sectional area accurately particularly difficult.

The volume of each disk was measured using a standard water displacement technique in which the disk is submerged in a container of water and the amount of water that it displaces is reflective of its volume. This procedure was extensively detailed to ensure that multiple team members could complete this process in a standardized way. A thorough explanation of the volume measurement method follows below.

The samples were first brought to a standard saturation by soaking in a tub of water for approximately 30 minutes. Weights were used to submerge the disks to ensure that they could become fully saturated. By fully saturating the samples, the team ensured that a uniform environment was created and an error was not introduced into the measurements because some samples absorbed more water than others.

A small metal bucket was placed inside of a larger bucket. The small bucket was gradually filled with water until the meniscus broke, indicated by a very small amount of water spilling over into the large bucket. The rim of the metal bucket was wiped dry between measurements to ensure that the spillover would be consistent between measurements, though this spillover may have introduced some error into the data.

The sample was carefully lowered into the water by hand until it was completely submerged. After submersion, it was lifted out carefully to avoid extra spillover. The small bucket was then removed from the large bucket. The water that had been displaced into the large bucket reflects the volume of the disk. This water was poured into a graduated cylinder, and the volume of water was recorded in milliliters. The volume was taken in this way until two measurements within twenty milliliters of each other were obtained. This redundancy ensures that the procedure was completed precisely. In the cases where the bark was separated from the log, the same method was used to measure the volume of the bark and this was added to the total volume for that specimen.

The variance in initial spill over and the initial dryness of the large bucket may have affected the data. The water sticks to the sides of the dry bucket more easily and therefore the first measurement using the dry bucket may have varied slightly from the others. Also, water may have stuck to the sides of the graduated cylinder and this could be a source of error. Water could also have stuck to the bottom of the small bucket when it was removed although attempts were made to shake off the water. When the logs were submerged into the water any extra splashing or force could have caused spill over as could our fingers when they were holding the log under the water.

3.2.1.3 Method for Drying Samples

After volume measurements were completed, each disk was dried in an oven for approximately 96 hours at 150°C before being weighed. This drying time was established by taking the mass of the disks periodically during the drying stage and drying to a constant mass. This methodology for establishing drying time was previously utilized by Sandstrom in decay experiments; the drying time for their samples was 48 hours at 85.8°C (Sandstrom et al., 2007). The team's samples were dried in order to make sure that the mass measured represented only the wood and not water that was absorbed while buried or during the volume measurement.

3.2.1.4 Method for Taking Mass Measurements

After being fully dried, the mass of each sample was measured using a small scale. Each sample was weighed individually, and the mass was recorded in grams. If pieces of bark had fallen off of the sample, but were buried as a part of the sample, these pieces were weighed together with the sample.

3.2.1.5 Method for Enclosing the Sample in Pantyhose

Prior to burial, each sample was confined within a piece of sheer pantyhose. The purpose of enclosing the samples within a breathable containment was to ensure that the sample would be fully recovered upon removal from the soil despite any decomposition. The pantyhose package controlled the bark that fell off of the samples, which was important for the accuracy of the mass and volume measurements that were taken upon the removal of the sample from the soil.

To secure the samples in pantyhose packages, the pantyhose legs were first cut into individual pieces into which a sample could be inserted. The ends of each pantyhose segment were secured with a simple knot. Each pair of pantyhose was cut into eight sections, each section to enclose one disk. Pantyhose were chosen as ideal for this purpose because they are elastic, sheer, and breathable.

The team believes that the presence of the pantyhose did not affect the reaction of the disks to the environments in which they were placed. In the literature, a similarity was found with the use of "leaf litterbags" while decomposition was being studied (Adair et al., 2008). The litterbags had a 1mm nylon mesh on the top, which allowed access by most soil fauna. On the bottom, the leaf litterbags had a thicker 55mm Dacron cloth which prevented losses from fragmentation but allowed access by other factors that may influence decay such as bacteria and protozoa (Adair et al., 2008). Like the leaf litterbags used, pantyhose are made of a thin nylon layer and thus should not have altered the decomposition of the samples.

3.2.2 Burial Methods

The disks were placed in various environments to observe the differing decomposition rates. Each data set contained five points which represent the different environments. Within each set, one disk was placed on the surface of the ground, three disks were buried underground at specified depths, which corresponded to the different soil horizons, and one disk was submerged in a nearby pond.

3.2.2.1 Ground Burial

Four of the five disks from each data set were located at the grassy field site at WREC. One of these disks was placed on the surface of the column, both serving as a marker for the column location and a control for the experiment. The disk on the surface of the soil is reflective of a dead tree that remains on the forest floor to decompose. Comparing the decomposition of this disk to the buried disk will test the validity of the hypothesis.

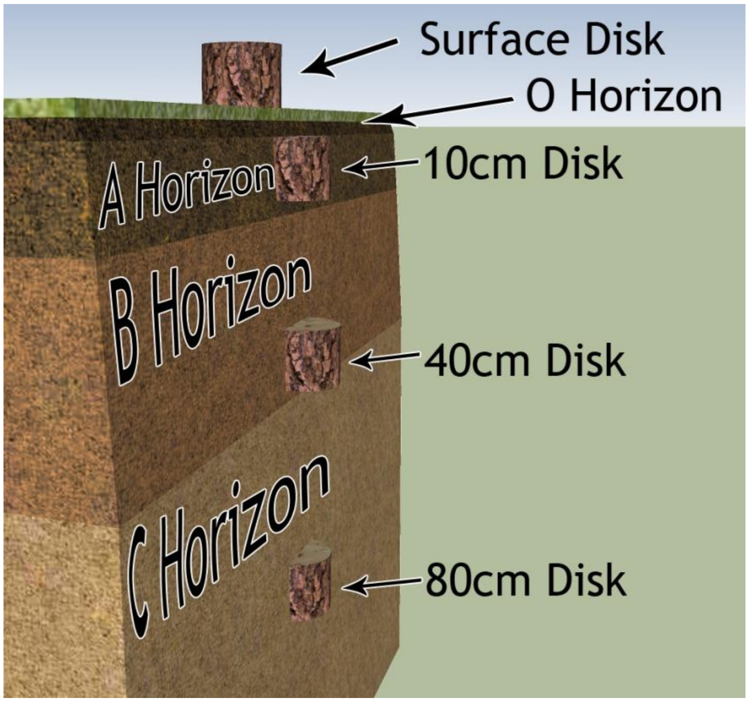


Figure 7: Cross section of soil with a single column of disks

The other three disks in a data set were buried at three depths: 10 cm, 40 cm, and 80 cm. These depths were chosen based on the different soil horizons in the site location at WREC. At 10cm the soil is primarily topsoil, at 40cm it is composed of clay, and at 80cm the soil is a silt-clay mixture and the water table is reached. These different environments may affect the rate of decomposition due to the presence of different levels of oxygen, nitrogen, organisms, or other factors. Sampling within each of these environments provided the team with data to identify the optimal conditions and depth for the sequestration of carbon. A single hole, 90 cm deep, was dug for each set of data. In total, 25 sets of data were buried at the field site, oriented as shown in Figure 8 below.

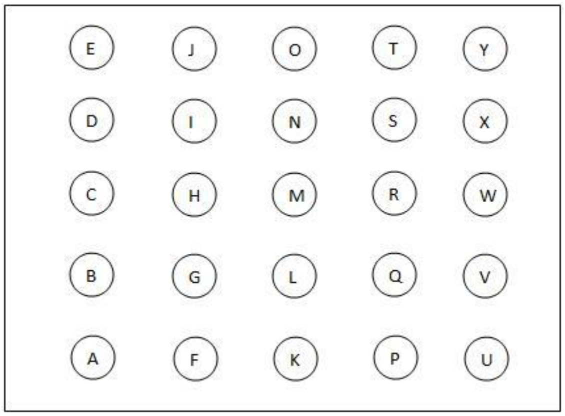


Figure 8: Top-down view of wood burial layout in soil

3.2.2.2 Water Submersion

In addition to the 25 sets of data (100 disks) buried as described above in the columns at the grassy site, 25 disks, also in panty hose, were submerged in a nearby pond in a modified oyster cage as shown in Figure 9. The cage was modified in such a way that the samples did not rest in the mud at the bottom of the pond but instead were suspended as close to the bottom as possible as shown in Figure 10. This setup was intended to simulate the extended exposure of disks to pond water, but to also make it easy to locate the disks at the bottom of the pond and remove them so that their decomposition could be evaluated. The temperature of the pond was monitored and recorded.

Figure 9: Modified oyster cage

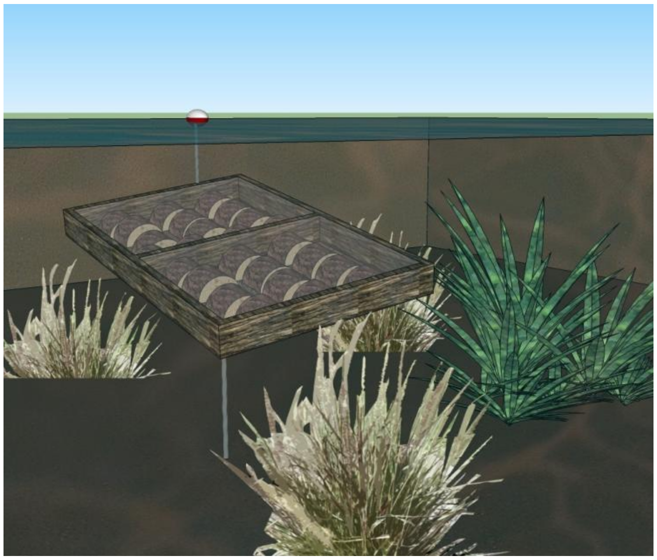


Figure 10: Depiction of water submersion method

3.2.3 Post-burial Methods

Every four months, when buried or submerged disks were recovered from their respective environments, measurements of both volume and mass were taken for comparison purposes and statistical analysis of decomposition. Before volume measurements were taken, a photograph of the disk was taken upon removal so that the physical condition of the decomposing disk was recorded, with the exception of the first set of disks removed.

The procedures for volume and mass measurements used prior to burial were replicated post burial to ensure consistency in the experiment. During post burial measurement, the procedure was slightly modified to account for pieces of detached bark and split wood disks. These pieces were significant and were therefore kept with their respective disk during the volume and mass measurements. In any case where loose pieces of bark were present with a disk or where the disk was split, this condition was noted.

Chapter 4: Lab Experiment

4.1 Lab Background

4.1.1 Overview

While the field experiment parallels the potential real world application of carbon sequestration by burial, it is limited to a very short period of time, about two years of testing. Usually, dead wood can take up to 20 years to significantly decompose (Kimmins, 1996). Because of this, we designed a lab experiment to supplement the data from our field testing, allowing us to accurately analyze biomass decomposition in a controlled environment. This lab setup allowed us to accelerate the decomposition process while manipulating environmental variables, in order to observe trends in a much shorter period of time. It also allowed us to reduce the number of variables that occur in a real world environment. It would have been difficult to account for the large variations in the field, so the lab experiment manipulated several variables that were assumed to have a significant impact on decomposition rate. The lab experiment's intention was to identify an optimal field environment for carbon sequestration.

4.1.2 Justification of Methodology

A chemical called soda lime was used in these simulated environments in order to measure the decomposition of the sawdust. Soda lime is a mixture composed mainly of calcium hydroxide and sodium hydroxide, which is capable of absorbing carbon dioxide from its environment (Grogan, 1998). When it absorbs carbon dioxide, there is an associated gain in weight; this is how the decomposition rates of the sawdust could be accurately measured. However, some of the weight gain observed is due to the production of one mol of water for each mol of CO_2 absorbed (For the full reaction pathway, see Appendix II) (Grogan, 1998). Also, soda lime cannot absorb carbon dioxide unless water is present, which is why beakers of water were placed in each of the controlled environments.

The gain in weight of the soda lime relates, by a relatively simple relationship, to the actual amount of carbon dioxide absorbed. Because of the chemical production of water, which is driven off by baking, the actual weight gain of the soda lime is less than stoichiometry would predict. Therefore, to deduce the actual amount of carbon dioxide absorbed, the gain in weight of the soda lime needs to be multiplied by a correction factor (Zibilske, 1994). Although Zibilske reported the correction factor to be 1.41, a later study found the actual correction factor to be 1.69 (Grogan, 1998).

This method was chosen for the lab experiment not just because of its simplicity, but because of its proven successes. Soda lime has been used for carbon dioxide absorption in many different applications, ranging from anesthetic procedures (to absorb the patient’s respired carbon dioxide), to deep sea diving, to soil analysis (Richardson, Menduno, & Shreeves, 1996). The process employed in the lab was relatively easy to conduct, as opposed to other methods of carbon dioxide detection, which usually require titration and/or expensive lab equipment. This was also beneficial because it eliminated potential human errors usually associated with titration.

4.1.3 Lab Description and Location

Dr. Bruce James, Director of Environmental Science and Policy at the University of Maryland, provided lab space to us, in his on-campus soil laboratory.

Dr. James gave us full access of his lab, including the use of a drying oven, incubators, and various testing materials. This provided us with a consistent, undisturbed, easily manipulated environment to run our tests. Below in Figure 11 are two photos of the equipment used in the lab.

Figure 11: Oven for baking soda lime at 100°C (left); Incubator at 35°C (right)

4.2 Experimental Setup

4.2.1 Materials

For the lab experiment, the team chose a setup that was not only simple and easy to implement, but also fairly inexpensive. All materials used were either provided for us by Dr. James or bought at Home Depot using funds generously provided to us by Gemstone. The setup consisted of 10 two-gallon buckets with sealable lids, 100mL and 30mL beakers provided by Dr. James, soil collected from our field site, and untreated pine sawdust donated by Home Depot. To maintain a greater degree of control, both the soil and sawdust were sieved; the soil to 4mm and the sawdust to 2mm. We chose pine so that we may more effectively relate the results from this lab experiment to the data we collected from the field, in which loblolly pine was used. We also employed the use of chicken manure as a fertilizer.

4.2.2 Basic Design

The lab experiment consisted of a series of ten microcosms, which were set up to mimic different environmental conditions. Although variables were changed throughout the experiment, every test run was based on a very simple design. Our control environments contained 400g of soil (from the same horizons used in our field experiment) distributed evenly across the bottom of the bucket, approximately 15g of soda lime in a pre-weighed 100mL glass beaker, and approximately 25mL of distilled H_2O in a 30mL beaker. The basic design is shown below in Figure 12.

Figure 12: Top-down view into control bucket

The control environments measured the background rate of soil respiration and provided a baseline with which to compare our results. Over the duration of this experiment, the soda lime was weighed, and the environments were refreshed (emptied, washed, and restored with new materials) every seven days.

The first basic manipulation tested was similar to the control, but with 20g of sawdust mixed into the soil. For these environments 400g of soil from each of the three horizons (A, B, and C) was placed evenly at the bottom of the bucket with the 20g of sawdust mixed evenly throughout the soil. Again a beaker filled with 25mL of distilled water was added to the bucket to drive the soda lime reaction and a separate beaker with 15g of soda lime was added to the bucket. Figure 13 (below) shows this set up.

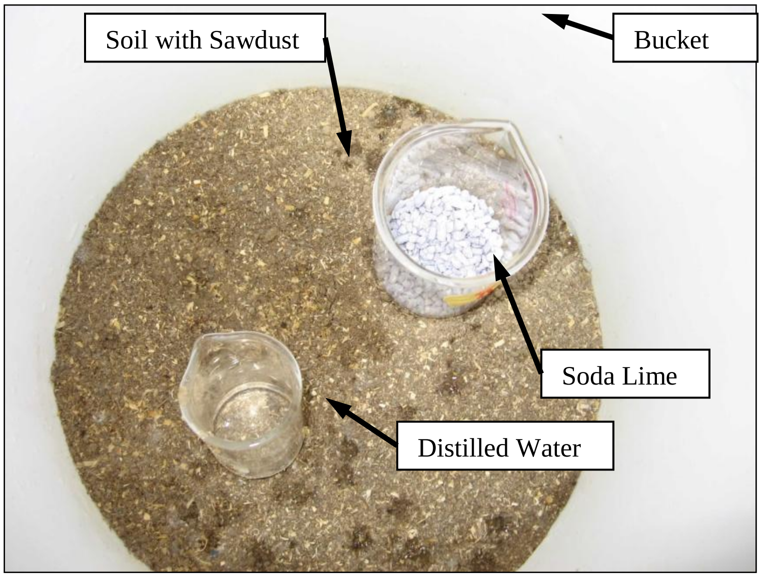


Figure 13: First basic manipulation

Once the buckets were properly prepared, they were sealed with an airtight lid, as shown in Figure 14, for a predetermined time period (typically 3 to 14 days depending on the conditions tested).

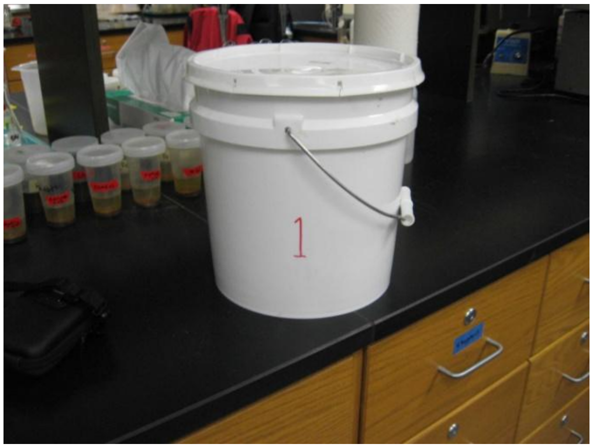


Figure 14: Bucket sealed with airtight lid

After the prescribed time period, any difference in weight gain by the soda lime between this manipulation and the control could reasonably be assumed to be due to carbon dioxide released through decomposition of the sawdust.

The second basic manipulation was similar to the first manipulation, but the buckets were also flooded with 200mL of distilled H_2O to simulate woody debris either at the bottom of a body of water or buried below the water table in the ground. These experiments are similar to the field experiments where the disks were placed below the water table or submerged in a pond. Like the first basic manipulation, these lab experiments consisted of 400g of soil from each soil horizon with 20g of sawdust mixed evenly throughout, 25mL of distilled water in a beaker, 15g of soda lime in a beaker, and 200mL of distilled water added to the soil. This additional distilled water created a soil that was completely saturated with water and gave it a “wet and muddy” consistency as shown in Figure 15.

Figure 15: Second basic manipulation (soil is completely saturated)

Additional manipulations involved placing microcosms in an incubator set at a temperature of 35^{o}C, adding 6g of a chicken manure based fertilizer, using soil from different horizons (A, B, and C), and soil saturation. A complete description of all manipulations tested can be found in Table 1.

For each time period, 10 microcosms containing the setups described above were tested. The experiments began by baking 11 beakers containing 15g of soda lime each. After 24 hours, these beakers were removed from the oven and placed in each of the ten microcosms (buckets). The 11th beaker was placed in the open air in the lab to act as a control. These buckets were then sealed with airtight lids and were undisturbed for the prescribed time period (typically 3 to 14 days). During this time period the microbes in the soil would react and decompose the sawdust and other organic matter in the microcosm. This decomposition would release carbon dioxide which would then be absorbed by the soda lime.

After the prescribed time period, the beakers of soda lime were removed from the buckets and placed in the oven at 100°C. After seven days, the soda lime was removed from the oven and reweighed to determine the amount of carbon dioxide absorbed. Before the next series of tests, each of the ten buckets was thoroughly washed and rinsed with distilled water, and the soda lime that was used in testing was properly discarded. This ensured that each new trial consisted of new soda lime and new environments in each of the buckets.

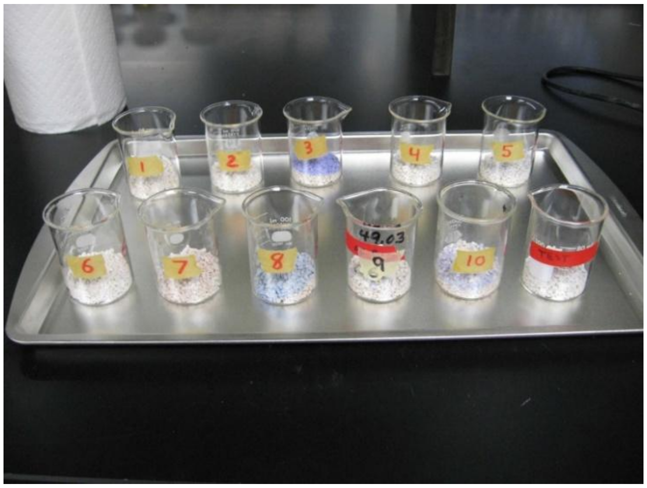


Figure 16: Beakers of soda lime before placement in oven

4.2.3 Variables Tested

One factor tested in our lab experiment was the type of soil used in each environment. Soil from horizons A, B, and C were individually tested in these microcosms in order to determine a relationship between soil type and decomposition rate. For each of the horizons we conducted 8 series of tests with each of the 10 buckets (80 tests for each soil horizon).

Another variable that was manipulated in these controlled environments was the water saturation of the soil. Some of the test environments included 200 milliliters of water, in order to emulate the water submersion test and burial below the waterline in the field. We determined that 200mL of water completely saturated the soil and created an experimental environment where the sawdust was submerged in water for duration of the experiment.

In addition to these tests, chicken manure was used as a fertilizer variable in several of the environments. The fertilizer added phosphorus and nitrogen to the environment, which are usually limiting nutrients in the decomposition process (Harmon, Krankina, & Sexton, 2000). The goal of using fertilizer as a variable was to determine if soil higher in nutrients would affect decomposition. Soils vary in their nutrient levels due to many factors. By testing decomposition under fertilization, we want to find out whether fertile soils are better or worse for carbon sequestration.

One final variable that was manipulated was the temperature of these miniature environments. In soils, temperature can vary based on many factors. Therefore, we incubated some of the microcosms at 35°C in order to determine the effect of varying temperatures on the decomposition rate of dead wood. The data collected from these microcosms were compared to the microcosms placed at room temperature of the lab (25°C).

A summary of the treatments used in the lab experiment are shown below in Table 1.

Treatment	Bucket	400g of 4mm sieved Soil	20g of 2mm sieved Sawdust	6g of Fertilizer	Incubated at 35^{o}C	Flooded with 200ml water
1	I	X	X			X
	II	X	X			X
2	III	X	X	X		
3	IV	X	X			
	V	X	X			
4	VI	X				
5	VII	X		X		
6	VIII	X	X	X	X	
7	IX	X	X		X	
	X	X	X		X	

Table 1: Experimental manipulations

The controls in each seven day trial were treatments 3, 4 and 5. Treatment 4 was our absolute control. It was tested in order to establish baseline soil respiration. Treatment 5 was our fertilizer control. It was tested in order to measure fertilizer respiration. Treatment 3 was our natural control. It was tested in order to observe sawdust decomposition without added variables. Treatment 1 was intended to simulate the wood buried in soil under the water table. Treatment 2 was intended to simulate wood buried in nutrient rich soil. Treatment 6 simulated wood buried in nutrient rich and warm soil. Treatment 7 simulated wood buried in warm soil.

4.3 Statistical Tests

In order to properly analyze how decomposition was affected by both soil horizon and each variable tested (addition of nutrients, temperature, and water saturation), an Analysis of Variance (ANOVA) was run. The ANOVA is a statistical technique which is often used to determine if there is a statistically significant difference between two or more means. We used the ANOVA to compare the mean percent changes of the three soil horizons, and, separately, the means of the seven treatments. Because we were testing soil from three different soil horizons, as well as seven unique treatments, an ANOVA was the most logical and time-efficient analysis to perform.

Specifically, we compared the mean of Treatment 3 (soil and sawdust) to that of Treatment 4 (soil only) in order to establish that at least some of the CO_2 absorbed by the soda lime was due to decomposition of the sawdust, and not solely due to background soil respiration. Next, we compared the means of all the other treatments to that of Treatment 3 in order to determine how each variable tested affected (increased, decreased, or no effect) decomposition. After the original ANOVA was run, Post Hoc Scheffe tests were performed for every pair of treatments in order to determine if the difference observed had less than a 1% chance of being due to random chance ($p < 0.01$).

Chapter 5: Computer Modeling

5.1 Background

5.1.1 Purpose of Modeling

Although the field and lab experiments used robust scientific methodologies to produce tangible results, they were executed on a small scale with only a few variables investigated a limited number of times. Given the monetary and time constraints of the project, testing any more parameters than the most basic physical and chemical properties for extended durations was not feasible. In order to extrapolate the results found in these experiments to a larger scale a computer model was used. A model allowed for testing multiple variables by altering the input to reflect changes in ambient conditions. The simulations generated by a model may be reproduced much more quickly than field or lab experiments and the cost of running individual iterations of a computer model is negligible. Although a model cannot consider all the variables that may affect a field experiment, such as the presence of microorganisms, a mean value from running multiple iterations would still be representative of a real world scenario because it takes into consideration randomness and variance.

The use of computer models for replicating environmental processes is not a new phenomenon. Scientists often employ the help of computer models to understand ecological phenomena. Some examples of these models are CENTURY, a model that simulates carbon, nitrogen, phosphorus, and sulfur dynamics, BIOME BGC, an ecosystem simulator that considers factors such as photosynthesis, and JABOWA, an iteration-based virtual forest simulator (Gilmanov, Parton, & Ojima, 1997; Chiesi et al., 2007; Botkin, 1993). Often, these models may be obtainable by their programmers and are open source meaning developers have access to the source code and may make changes to it as fits their research needs.

5.1.2 Basis of Computer Model: JABOWA version 3

5.1.2.1 Introduction of the JABOWA Model

Since most researchers on Team Carbon Sinks had minimal programming expertise, building an original and functional computer model was impractical. The best option was retrofitting an extant open source model. Out of the possible models that could be used for this research project, JABOWA dealt directly with forest growth and could be utilized to understand the sequestration potential of forest plots. Additionally, Dr. Zeng had acquired the source code and a registration key for the latest version of JABOWA while involved in previous research endeavors.

The JABOWA program was first coded and published in the early 1970s by Daniel B. Botkin and his colleagues, James F. Janak and James R. Wallis (Botkin, 1993). JABOWA III, the most recent version, is designed to accurately simulate how trees would grow on a given plot of land. Scientists studying a select process within forests can use the model to visualize the process without having to spend many years in the field, and researchers interested in inserting their own variables can do so by modifying the source code. When executed, JABOWA creates a graphical output that illustrates the growth of trees on the plot, exemplified in Figures 17 and 18.

```
Habitat: NORTHEASTERN_DECIDUOUS_FOREST
Weather: NORMAL_CLIMATE
Year: 1990
Tree Legend:
  Pin_Cherry (bitmap)
  Choke_Cherry (bitmap)
  White_Birch (bitmap)
  Jack_Pine (bitmap)
  Red_Pine (bitmap)
  Gray_Birch (bitmap)
```

```
Habitat: NORTHEASTERN_DECIDUOUS_FOREST
Weather: NORMAL_CLIMATE
Year: 2030
Tree Legend:
  Sugar_Maple (bitmap)
  Beech (bitmap)
  Balsam_Fir (bitmap)
  Red_Spruce (bitmap)
  White_Birch (bitmap)
  Jack_Pine (bitmap)
  White_Pine (bitmap)
  Eastern_Hemlock (bitmap)
```

Figure 17: Graphical display of JABOWA model running simulation over 40 year interval

```
Habitat: NORTHEASTERN_DECIDUOUS_FOREST
Weather: NORMAL_CLIMATE
Year: 2070
Tree Legend:
  Sugar_Maple (bitmap)
  Beech (bitmap)
  Jack_Pine (bitmap)
  White_Pine (bitmap)
```

Figure 18: Graphical display of JABOWA model after 80 year simulation

5.1.2.2 Limitations of the JABOWA Model

As a "gap" model, JABOWA models forests on an individual tree-by-tree level, creating the forest by attempting to model the interactions between different trees in a 10m x 10m plot of forest. An important assumption made by JABOWA is that all trees in this plot are presumed to affect all others equally while trees between different plots are presumed not to affect each other at all. This piecemeal approach was one way to tackle the problem of the finite computational abilities of the computers; the individual characteristics of each tree and the direct interplay between neighbors are ignored. All tree interactions are averaged out over the size of the plot, otherwise known as "parameterization." The 10m x10m plot size was chosen because it is the minimum size at which any two large trees inside the plot could conceivably directly affect each other’s growth, i.e. two trees within this size plot could hinder one another from access to sunlight. One final assumption made by the model is that a tree's leaves are all concentrated at its canopy. This simplification allows for easier computation than calculating the interplay of light off of every leaf, but may obviously introduce some amount of inaccuracy to the model (Botkin, 1993).

The JABOWA forest simulation has an iterative design. For each set of selected parameters for which data is desired, multiple program "iterations" are necessary. A full execution of the model will produce a single set of data. However, this data set considers only one group of randomized conditions and cannot be prematurely accepted as true for all forest plots with similar parameters. Subsequently, multiple executions/iterations of the model are necessary for statistical significance. After many iterations, the mean results can be more confidently projected onto all forest plots with the selected parameters.

The JABOWA program is acknowledged by its creators to be at best accurate to within 10% (Botkin, 1993). Even at its best, JABOWA's simulated forests can come only approximately close to empirical data collected from real forests. The uncertainty of all results proceeding from JABOWA and the Carbon Sinks alteration of the model must therefore be understood to be greater than 10%.

While JABOWA does have its limitations, it is still able to accomplish the research objectives of this project while providing much power and flexibility. When constructing plots, it takes into consideration internal factors like climate and tree species as well as external factors such as logging or natural catastrophic deaths of trees. These components of the JABOWA program demonstrate an appreciation for the wide applicability JABOWA has for related research.

5.2 Modeling Methodology

Despite its shortcomings, the JABOWA model was still very suitable for this research project. We used total forest biomass as a measure of the sequestration potential of the forest because any trees that grew within the forest plot would eventually contribute to the decomposing tree pool. Subsequently, determining which individual trees were alive was not as important as figuring out how many trees had died and their total carbon sequestration potential. However, JABOWA is a model primarily concerned with forest growth. Upon death, trees are merely deleted from the program's memory–dead trees are assumed not to interact either with living trees or each other, as their biomass becomes irrelevant to track for the purposes of forest growth. Forest carbon and nitrogen recycling from the dead trees is assumed; it is parameterized.

From a programming perspective, our solution to deal with tree removal after death was to create a similar parallel structure to tree growth for dead trees. When trees died in the tree growth structure, they are moved to the death structure. Within the growth structure there are several places where a tree could die such as logging, windthrow, or natural aging. Additionally, every year, when live trees' growth is simulated the incremental decay of the dead trees is also simulated. This results in a continuously increasing total live biomass and continually decreasing dead biomass.

Periodically, trees may die which will cause a steep drop in the live total biomass pool and a spike in the dead biomass.

JABOWA keeps track of the biomass stored in the different parts of a given tree: its stem, branch, leaf, and root biomass. Leaf litter falls in an uncontrolled fashion and decays at a rate assumed to be roughly equivalent to composite surface litter decomposition. In addition, our experimental treatments affecting decay rate were supposed to emulate physical treatments. These treatments would be concerned mostly with where the majority of the mass was stored, as it would be impractical to collect all the needles of a pine and subject it to a physical burial. In the same way, the root biomass of a tree is difficult to remove and is already interred–subjecting it to decay treatments would be theoretically possible but impractical.

The original species set did not include loblolly pine, which is what was used for the field experiment, so it was added to the model. Daniel Botkin designed the JABOWA model such that developers can create their own species with the necessary values. The loblolly pine species was added in this fashion with predetermined values for the necessary parameters. The most important variables for creating a tree in JABOWA are ones directly related to the growth of a tree: the maximum diameter at breast height (DBH), maximum height, maximum age, and three proprietary parameters that were defined specifically for JABOWA. The values for maximum DBH, height, and age for loblolly pine were found in an online United States Department of Agriculture Forest Service database and are 1.35m, 45.7m, and 240years, respectively (United Stated Department of Agriculture Forest Service, 2009). The other three parameters were described in the JABOWA supplementary text and include biomass constant (B2), biomass constant (B3), and growth constant (G). The two biomass constants are used to relate the height of a tree to its diameter via the function:

$$H(D) = 137 + b_2 D - b_3 D^2$$ (Botkin, 1993)

This formula relating tree diameter to height has existed in the scientific community for a substantial time, and it has been confirmed from various research teams (Ker & Smith, 1955). The equation for biomass constant (B2) is:

$$b_2 = \frac{2(H_{max} - 137)}{D_{max}}$$ (Botkin, 1993)

where H_{max} and D_{max} are the maximum height and maximum diameter in centimeters. On the other hand, the equation for biomass constant (B3) is:

$$b_3 = \frac{2(H_{\mathrm{max}} - 137)}{D^2{}_{\mathrm{max}}}$$ (Botkin, 1993)

Given its maximum diameter and height, the biomass constants for loblolly pine were found to be 65.674 and 24.3m-1 for B2 and B3. The value for G was not as easily determined. It is related to how quickly the tree species grows and is slightly more arbitrary. The text offers a formula for the growth constant:

$$G \approx 5H_{max}\left(\frac{\delta D_{max}}{D_{max}}\right)$$ (Botkin, 1993)

However, the formula requires knowledge of the max incremental diameter growth (δD_{max}) of the species which would have required additional field testing on loblolly pine trees. Fortunately, in an email correspondence with Dr. Botkin, he noted that the growth factor can be found by comparing the species of interest's demography and physical ecology to an included tree species that is in the same genus (D. Botkin, personal communication, February 17, 2010). We decided that white pine (Pinus *strobus*) has the closest growth characteristics to the loblolly pine (USDA Forest Service, 2009). The growth constant for this species was initially used to create a forest which was juxtaposed to our known values for the height, diameter, and age of loblolly trees. Then the G was modified until the simulated stand grew similar to what would be expected in an actual plot. The final calculated growth constant was approximately 95. Apart from these six parameters, each tree in the JABOWA code had several other variables. These values were less variable, and averages of like species were used for most of them. After finding the parameters for loblolly pine, a complete forest of loblolly could be simulated and used to extrapolate the information that was acquired from the field experimentation. The altered program, for clarity, will hereby be referred to as JABOWA-Carbon Sinks, or JABOWA-CS.

5.2.1 Mathematical Models of Decomposition

As mentioned above, Carbon Sinks was responsible for implementing dead tree decomposition in a modeling environment. After dead logs were moved to a separate data structure, all that was left was to determine the manner in which each log decomposed. We settled on a log-by-log method of decay, considering each dead tree separately (mirroring the living tree model). However, much like growth in JABOWA, all dead logs' decay behavior is treated identically and decay behavior across all logs is parameterized. This means we chose to find a single mathematical decay model that could be applied to a single log and extrapolate this model to all logs within our forest. It then remained to be determined what sort of mathematical model we would use.

5.2.1.1 Single Litter Pool vs. Multiple Litter Pools

Most published research suggested that woody biomass decays at an exponential rate, and for many species it is beneficial to include an exponential function for each of the major chemical components of a tree (Adair et al., 2008). Lignin and cellulose compose a large proportion of most woody biomass, but the two different molecules decay by different mechanisms and experience very different decay rates. For some species of trees, a model incorporating three separate exponential functions modeling different "pools" of biomass was found to more accurately represent decomposition than formulas that included only one or two single exponential function (Adair et al., 2008). In addition, there are physical reasons for the differing decay rates of wood–older trunks of most trees are divided into heartwood (older wood central to the tree, present primarily for structural stability) and sapwood (living wood that still conducts nutrients). The tree deposits high concentrations of chemicals toxic to microbes and fungi in the heartwood, rendering it more resistant to decay (Scheffer, 1966). This might also result in a decay curve best modeled by multiple-pool exponential models.

However, loblolly pine is a softwood. Many of the most quickly growing trees of this species lack heartwood and what heartwood there is, is classified as having "moderate to low" resistance to decay (Radtke et al., 2009; Alden, 1997). Additionally, most literature found addressing the question of the decay of loblolly woody debris used the single-exponential model of decay (Radtke et al., 2009; Binkley, 2002). Not wanting to depart too far from the baseline models of comparison, we chose to utilize a simple exponential model of decay. Radtke et al. note that quickly grown, younger loblolly (plantation trees) trees lack significant heartwood, and for these trees a single exponential decay model is sufficient. Our examination into carbon sequestration capacity does not restrict the age of the tree; thus, some of our simulated trees should indeed have significant amounts of heartwood. The form of our mathematical model is thus:

$$M_{t+1} = M_{\mathrm{t}} \cdot \alpha$$

where alpha (α) corresponds to the decay constant (i.e. the fraction of mass remaining after one year of decay). This model is discrete time as JABOWA calculates decay discretely year by year. Given that the total biomass decreases over time, the decay constant will always be less than one.

5.2.1.2 Limitations of Selected Decay Model

Decaying trunks in the JABOWA-CS model are subject to a number of simplification assumptions, much like that of the growth model in JABOWA. All trees decay according to a simple exponential model. This implies that we treat the trunks of trees as identical samples homogeneous wood. The details of how differently sized pieces of wood might affect the decay rate are "parameterized;" surface area doesn't directly impact our equations. For the purpose of our model, decaying trees are also assumed to affect neither each other, nor the living trees. Because it is carbon content and not biomass that we are ultimately concerned with, we must address the fact that the carbon content of the decaying biomass may not remain strictly constant throughout the decay process. However, analyses in other studies have shown that carbon content is roughly 50% in all parts of a tree, even decayed trees (Kinerson, 1975). Although these assumptions do not establish a completely realistic scenario, the model is still capable of making a good approximation of our results.

5.2.2 Modeling Experiment

Once the modeling environment was established, research questions could be asked, and research objectives were identified. We asked to what degree the decay rate of woody debris in a loblolly forest affects the carbon sequestration potential of the forest. We then used JABOWA-CS to grow simulated loblolly forests, track the natural death of the trees, and then subject the dead trees in the simulation to different decay rates.

5.2.2.1 Independent Variable

The independent variable used in this study was the decay rate. If the decay rate of the naturally dying wood in a simulated JABOWA-CS loblolly forest could be altered, it would simulate the effects of wood burial, removing wood from the natural environment and artificially subjecting it to conditions in which its decay rate would be reduced.

Depending on the treatment type, the decay rate of stem and branch biomass was altered to reflect the treatment. Root and leaf biomass is not meant to be subjected to our treatment, and was assumed to decay at a constant rate.

Three separate decay rates in particular were analyzed. The decay rate of loblolly debris lying on top of the forest floor is approximately 15% per year (Binkley, 2002). In the Binkley study, this rate was actually found in reference to the conglomerate of organic matter found lying at the forest floor of a loblolly forest, but it correlates well with the rough decay rate found for the logs in Team Carbon Sinks' field study. This would refer to the sum of stem, branch, and leaf litter lying on top of the ground. Leaf litter is then assumed to always decay at this rate, regardless of the treatment type.

For below ground decay, a study by Ludovici, Zarnoch, and Richter (2002) found that taproots in the loblolly forests of central North Carolina decayed at a rate of about 5% per year. This corresponds well with our 26 year e-folding measurement of the decay rate of interred wood. This measurement is the time interval in which biomass decreases by a factor of e, and on the e-folding unit scale it corresponds to a 4% loss per year of biomass. Again, these numbers match after the large uncertainty in the Carbon Sinks decay rate is considered. Root biomass is always calculated to decay at this rate, regardless of the treatment.

Finally, we analyzed the decay behavior of a forest subjected to a hypothetical 0.1% per year decay rate. This decay rate is not outside the bounds of reason–many studies have shown that at low temperatures, the rate of decomposition of any biomass, including wood, approaches zero. Likewise, our snapshot of belowground decay does not exclude the possibility of low decay rates (less than 1%) achieved solely through internment under the C horizon of soil. Our hypothetical case was created mostly to offer an estimate of forest carbon sink potential. It provides goals for future investigations into the minimization of the decay rate of woody debris.

5.2.2.2 Dependent Variable

The dependent variable is the biomass stored in the forest. More specifically, the biomass of the forest is the sum of all root, stem, and branch biomass values for all decayed trees across all plots and iterations in the current simulation. This conglomerate value is reported by JABOWA-CS in units of kg/m^2, although we post process this value into units of metric tonnes/km^2. Therefore it is independent of the number of simulation iterations, and running more iterations results in a less statistically variable number. The number of iterations used for each experiment was 1000, creating a more statistically consistent forest.

After growing our forest, we were ultimately concerned with the amount of carbon stored in the forest, not just the weight of the woody biomass. However, there is a very strong and simple relationship between the mass of a tree and its amount of carbon. Additionally, the carbon content of the tree does not vary much between its different parts. The mass fraction of carbon in loblolly trees is 49% +/-2.3% (Kinerson, 1975).

It must be remembered that the dependent variable is not a static number, but rather a variable that changes with time. Forest biomass content changes as forests are grown, trees die, and decay treatments are applied, it must be given time to reach equilibrium. While the equilibrium state can often be reported as a single number regardless of time, the behavior of the forest in reaching that state is often just as interesting.

Chapter 6: Results and Analysis

6.1 Field Experiment Results and Analysis

The field experiment began on April 9, 2008 when we buried 125 half wood disks of loblolly pine at WREC. These disks were uncovered at four month intervals, and their masses and volumes recorded. As the previous methodology described, we buried disks at the O, A, B, and C horizons and submerged a set of disks in a pond at WREC.

This results section will present and analyze this field data in three parts. First, the general trends between the decomposition over time and the soil layer where the disk was buried will be presented. Second, possible explanations of the observed trends in decomposition will be offered using climate data taken throughout the experiment. Finally, the properties of each soil horizon will be related to the overall results.

6.1.1 General Trends of Each Soil Horizon

As the methodology section described, every four months five disks were uncovered from each soil horizon. These disks were then dried for several days in an oven and weighed. Using this data, the percent change in mass normalized by the original mass was plotted against the time when the disk was uncovered. An example of this can be seen below in Figure 19.

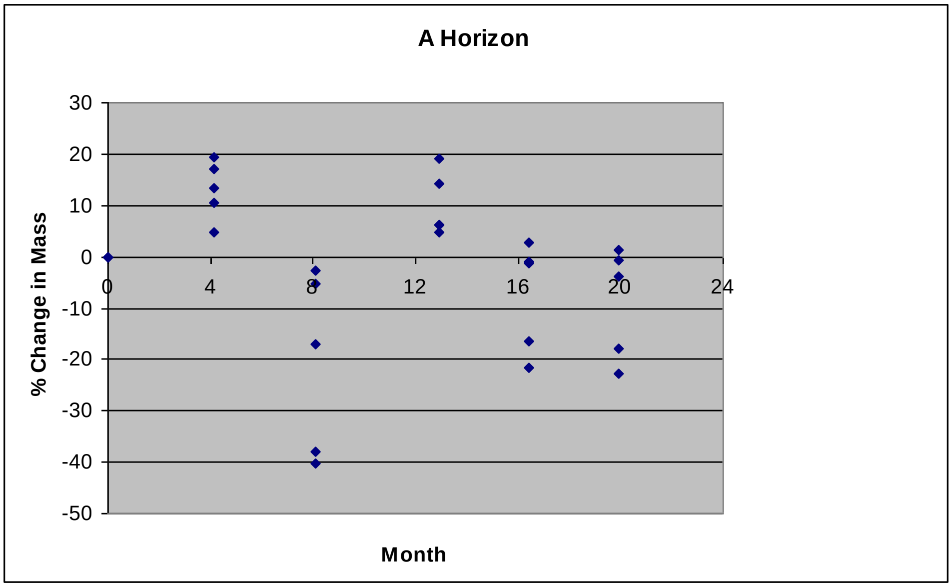


Figure 19: Percent change in mass versus time for A horizon disks

Three different methods of analysis were used to provide trends for this observed data for each soil horizon. The first was a linear regression model based on the assumption that the disks would decompose uniformly over time. Figures 20 – 24 show the linear regression and equation for each soil horizon.

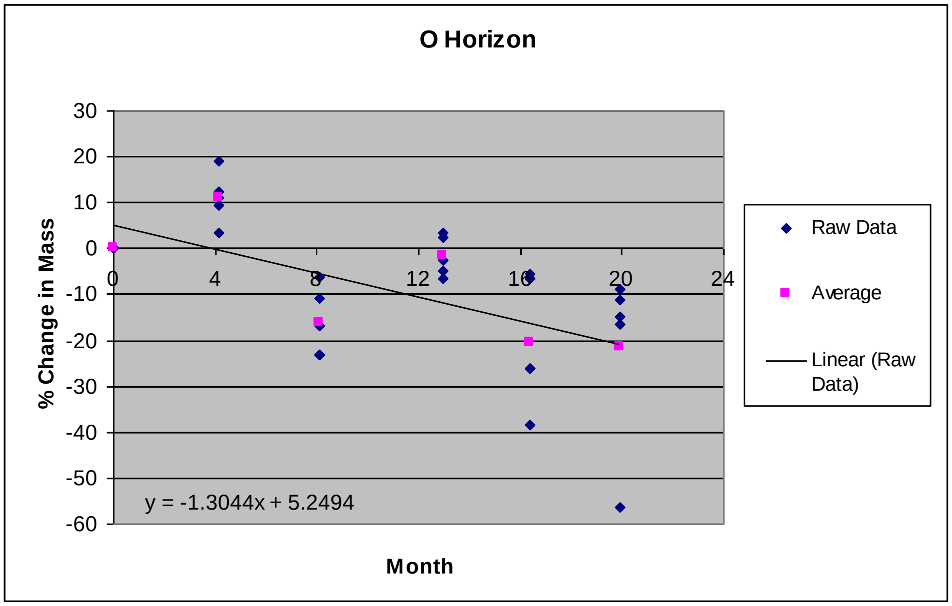


Figure 20: Percent change in mass versus month for O horizon disks with linear regression

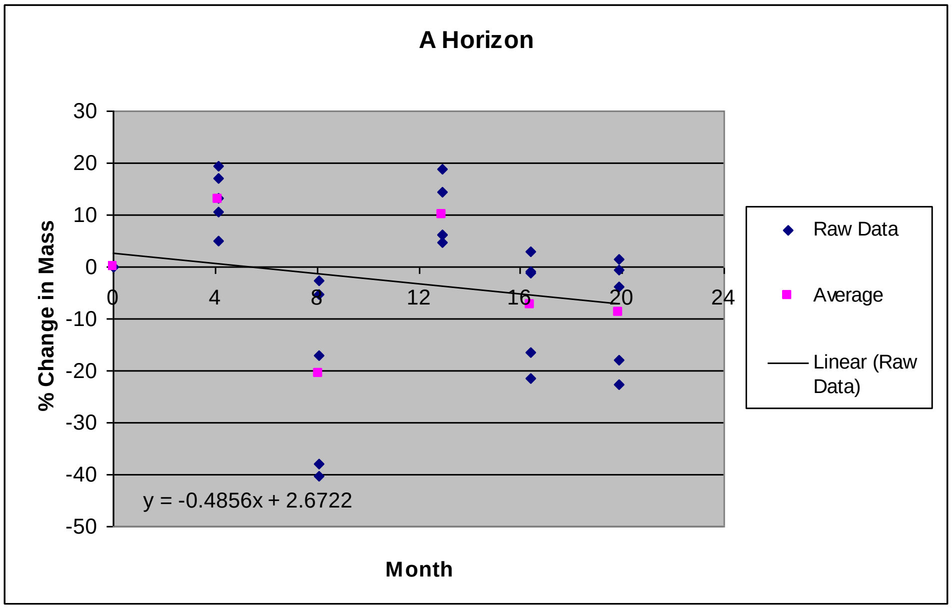


Figure 21: Percent change in mass versus month for A horizon disks with linear regression

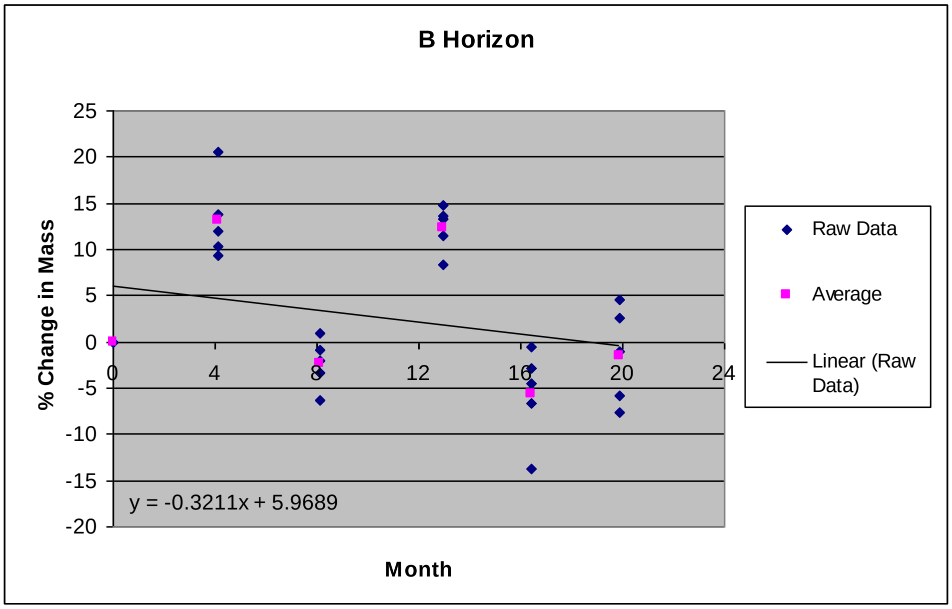


Figure 22: Percent change in mass versus month for B horizon disks with linear regression

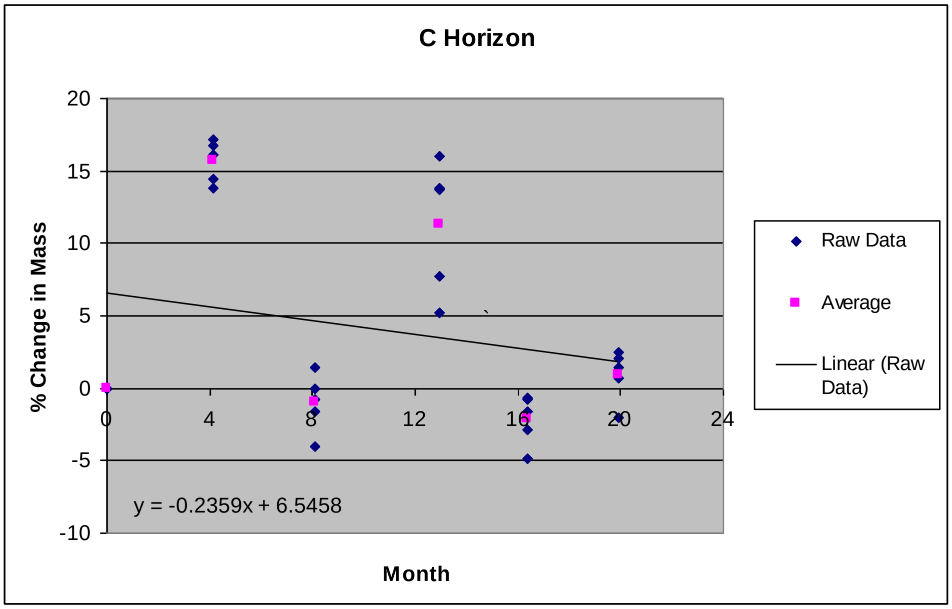


Figure 23: Percent change in mass versus month for C horizon disks with linear regression

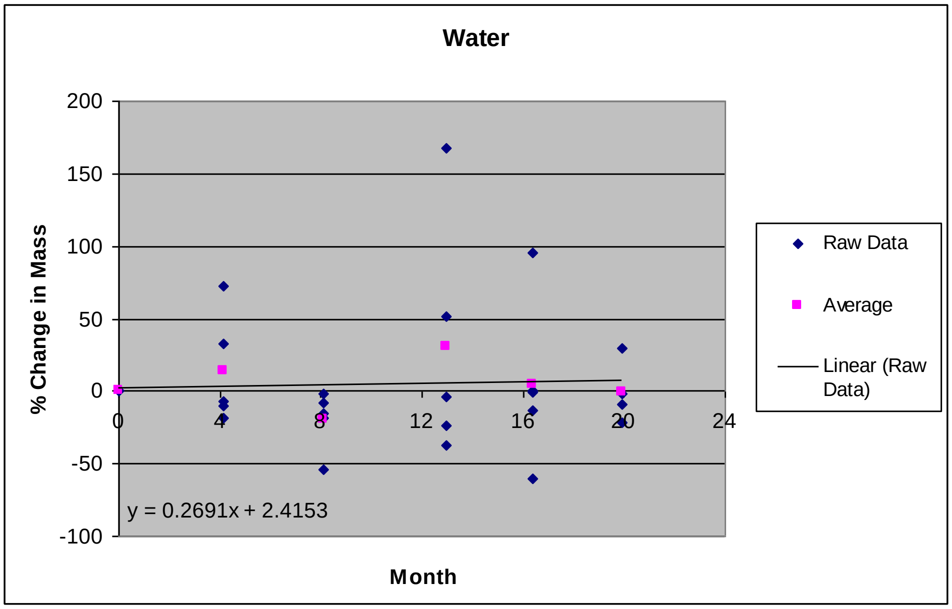


Figure 24: Percent change in mass versus month for submerged disks with linear regression

In these linear regressions a line of the form

$$y = mx + b$$

was used to fit the data. The most notable term in this equation is *m*, which represents the percent change in mass per month. As the above plots show, the disks on the surface (O horizon) had a rate of decomposition of 1.30 percent per month. This rate of decomposition is almost one order of magnitude greater than the rate of decomposition of the disks buried beneath the surface (A, B, and C horizons) which had decomposition rates of 0.49, 0.32, and 0.24 percent per month respectively. This basic linear trend suggests that burying the wood disks slowed down their decomposition.

The final plot of the disks submerged in water showed a rate of decomposition where the disks actually gained weight each month (0.27 percent per month). Initial visual observation of the disks when they were removed from the water showed that the disks had undergone some decay; this positive decay rate shows that there were some errors in this portion of the field experiment. A discussion of these errors is presented at the end of this section.

While the above linear regressions show basic trends of the data, the data appears to oscillate every four months. This oscillation may be caused by some seasonal trend, and the second method of analysis was to apply a least squares regression using an equation taking into account this seasonal cycle. The least squares regression equation used was

$$y = a_0 + a_1 t + a_2 \sin(2\pi t / T + \phi)$$

In this equation, T is the period, φ is the phase shift, and a_2 is the constant in the cyclic term. Since it is assumed that the disks' mass will decrease over time, a linear term $a_0 + a_1 t$ was added to the cyclic term. Using least squares regression to optimize the constants and minimize the square of the errors, the following plots were created. Note in the legend the blue line is the curve for the optimal least squares regression equation where the period T is a variable and the purple linear line is the line from the linear terms in the regression equation ($a_0 + a_1t$). Figures 25-29 show the harmonic regression and equation for each soil horizon.

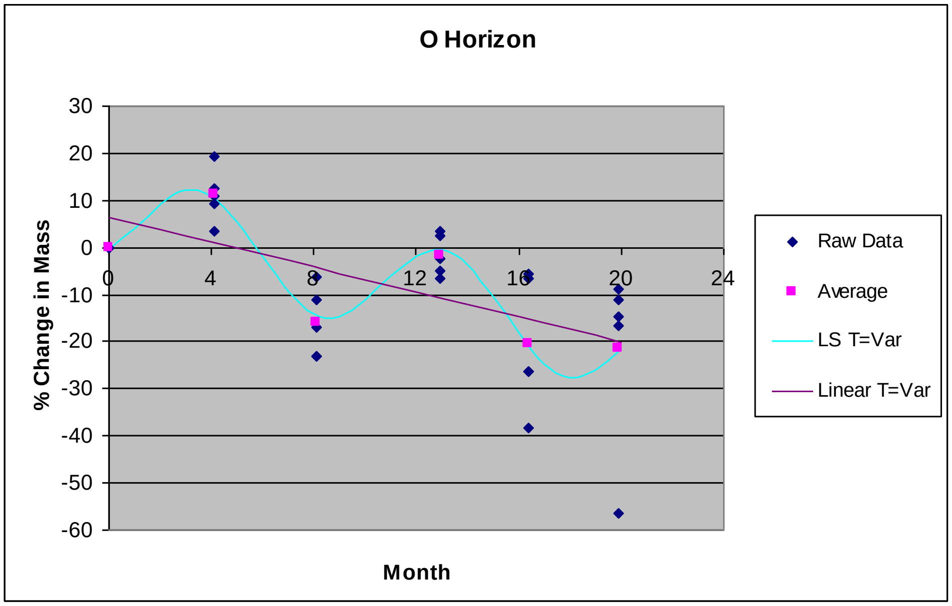


Figure 25: Percent change in mass versus month for O horizon disks with harmonic regression

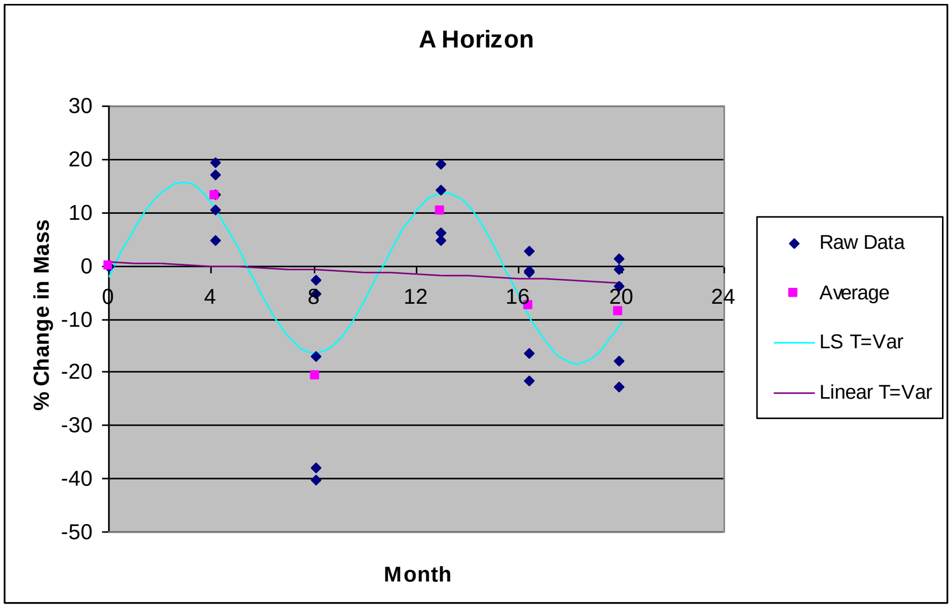


Figure 26: Percent change in mass versus month for A horizon disks with harmonic regression

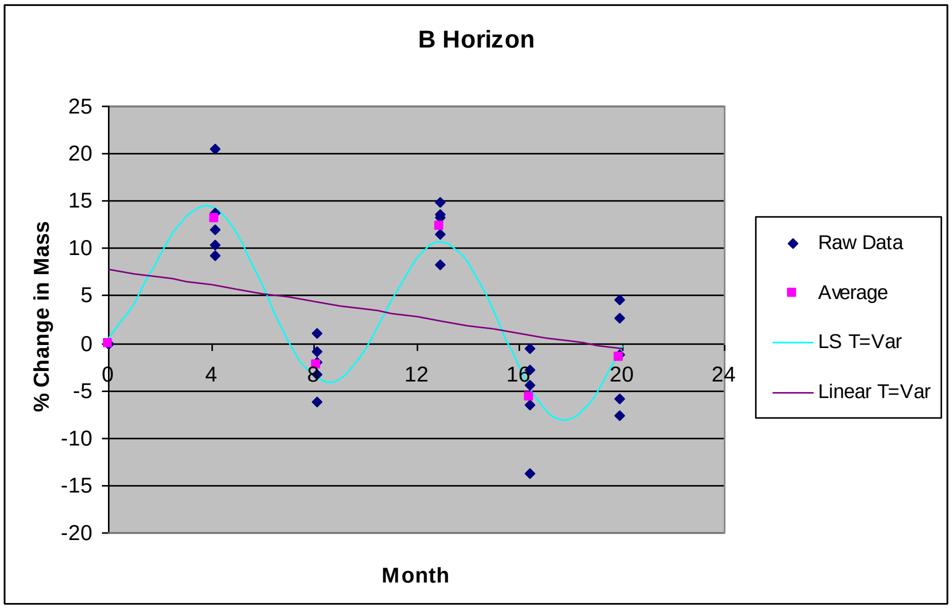


Figure 27: Percent change in mass versus month for B horizon disks with harmonic regression

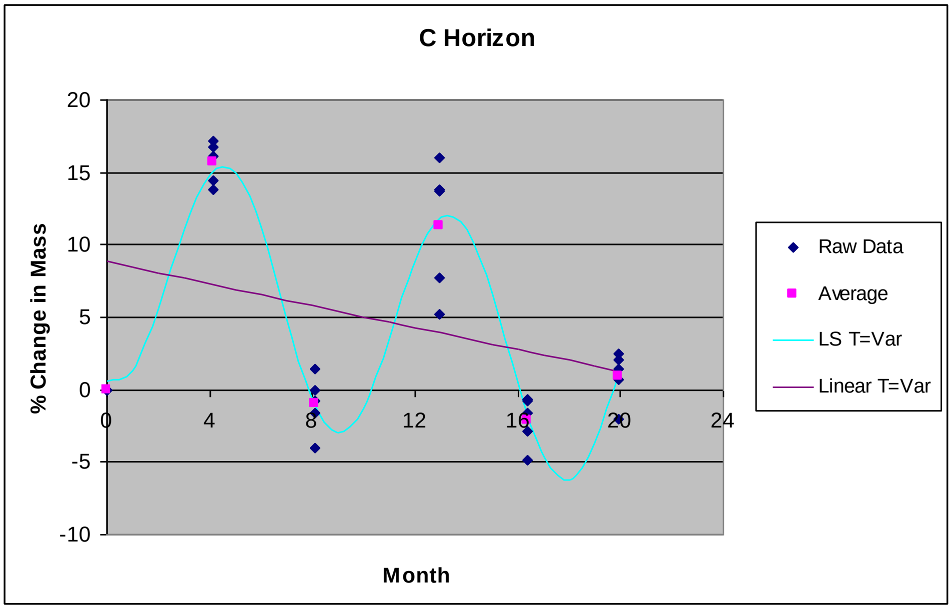


Figure 28: Percent change in mass versus month for C horizon disks with harmonic regression

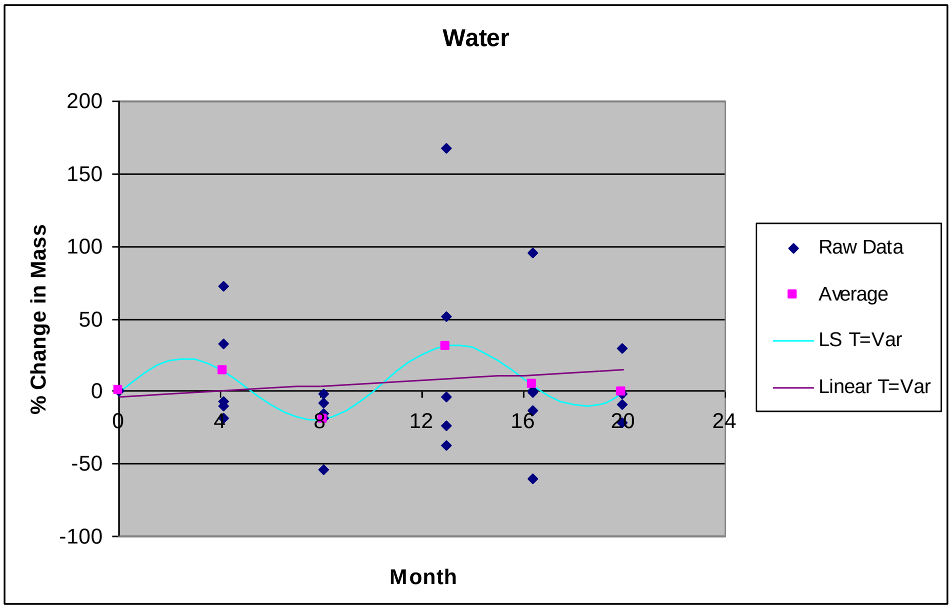


Figure 29: Percent change in mass versus month for submerged disks with harmonic regression

The constants determined from the least squares analysis for Figures 25 – 29 are summarized below for the equation

$$y = a_0 + a_1 t + a_2 \sin(2\pi t / T + \phi)$$

	Horizon				
	O	A	B	C	Water
a_0	6.44	0.76	7.82	8.83	-3.38
a_1	-1.32	-0.19	-0.42	-0.38	0.92
a_2	10.21	15.53	-8.35	8.37	23.56
φ	-0.74	-0.18	-4.21	-1.73	0.12
T	9.55	10.25	9.19	8.78	10.70

Table 2: Constants from least squares analysis of linear regression

Table 2 shows similar results to the linear regression performed earlier. The a_1 constant, which represents the slope of the cyclic function, shows that rate of decay for the disks on the surface (horizon O) had a rate of decay that was typically one order of magnitude greater than the disks buried in the ground (horizons A, B, and C). The submerged disks again showed a mass change rate that was positive (meaning the disks gained weight over time); this positive rate can be attributed to several errors which are discussed later in this section.

A second term of interest in Table 2 is the optimal period. Typically for all of the soil horizons, the optimal period was around nine or ten months for the curve to best fit the data using a least squares regression. However, intuitively, the optimal period would be expected to be twelve months to represent the full seasonal cycle of a year. The optimal period found through the regression is largely affected by the sample size, which is only twenty months. Furthermore, several factors including different rainfall and climate conditions during the twenty month experimental time period would also impact the optimal period size. However, to address the issue that the period should be twelve months, the third method of analysis performed was a least squares analysis on the same equation below, with the exception that T is set to a value of twelve months.

$$y = a_0 + a_1 t + a_2 \sin(2\pi t / T + \phi)$$

Figures 30 – 34 summarize the results of these regressions (the yellow curve is the least squares regression using a period of twelve months and the brown line is only the linear terms from the regression).

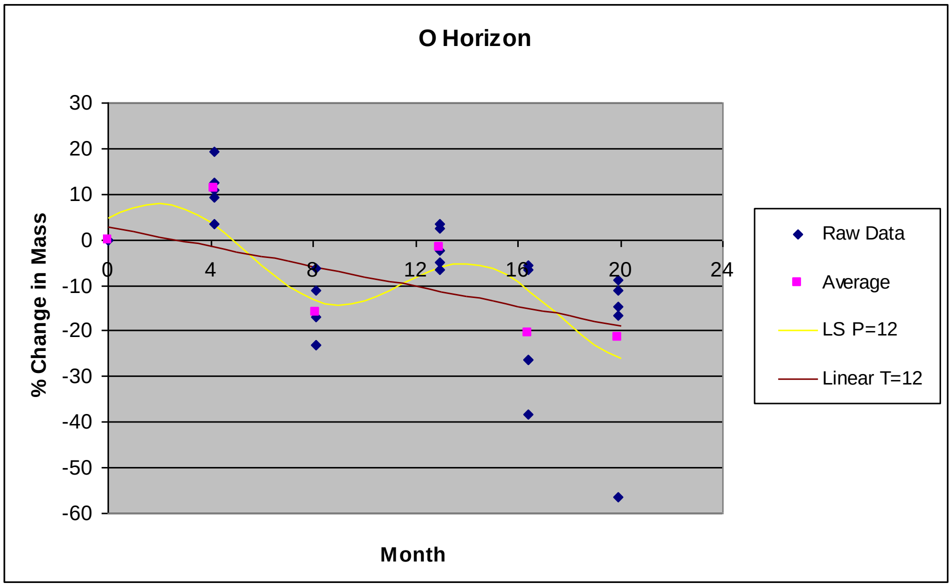


Figure 30: Percent change in mass versus month for O horizon disks with harmonic regression, T = 12 months

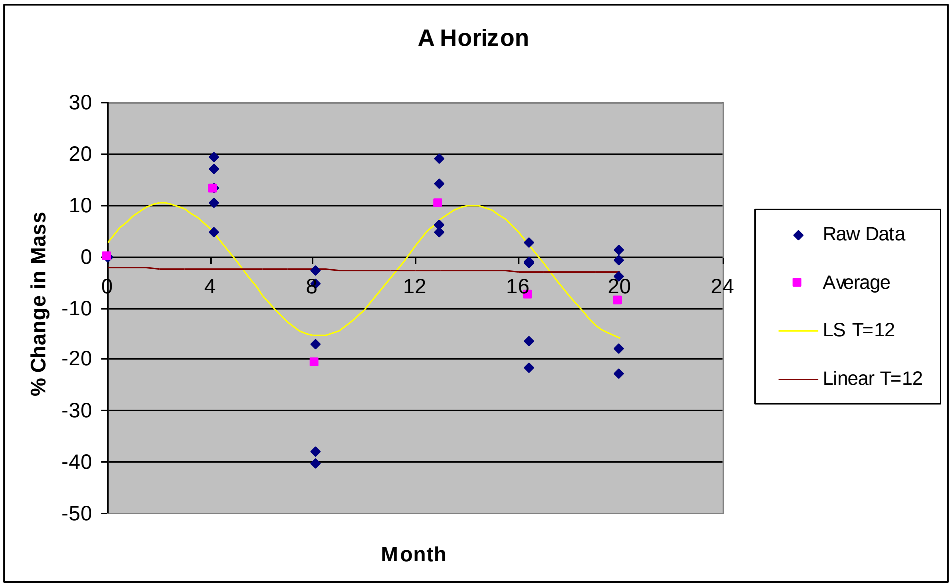


Figure 31: Percent change in mass versus month for A horizon disks with harmonic regression, T = 12 months

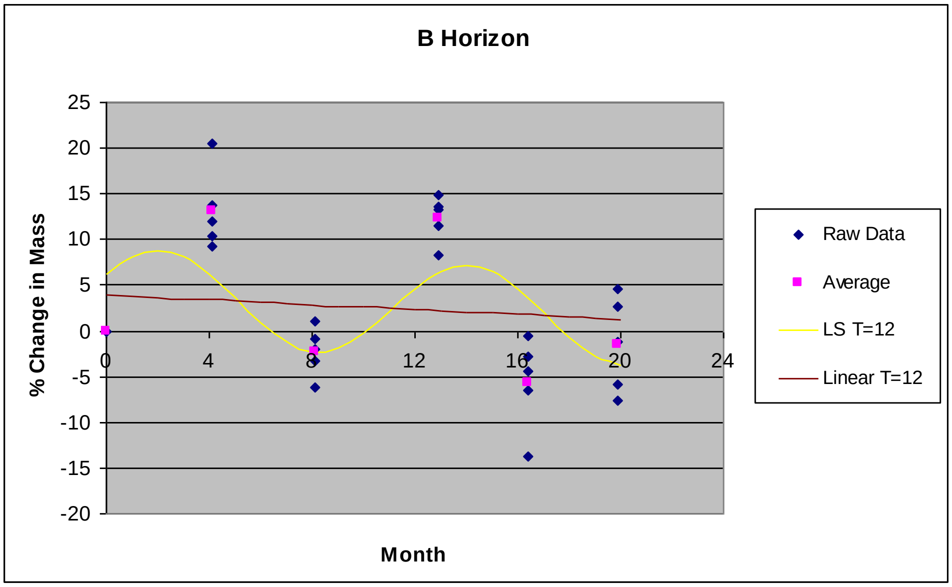


Figure 32: Percent change in mass versus month for B horizon disks with harmonic regression, T = 12 months

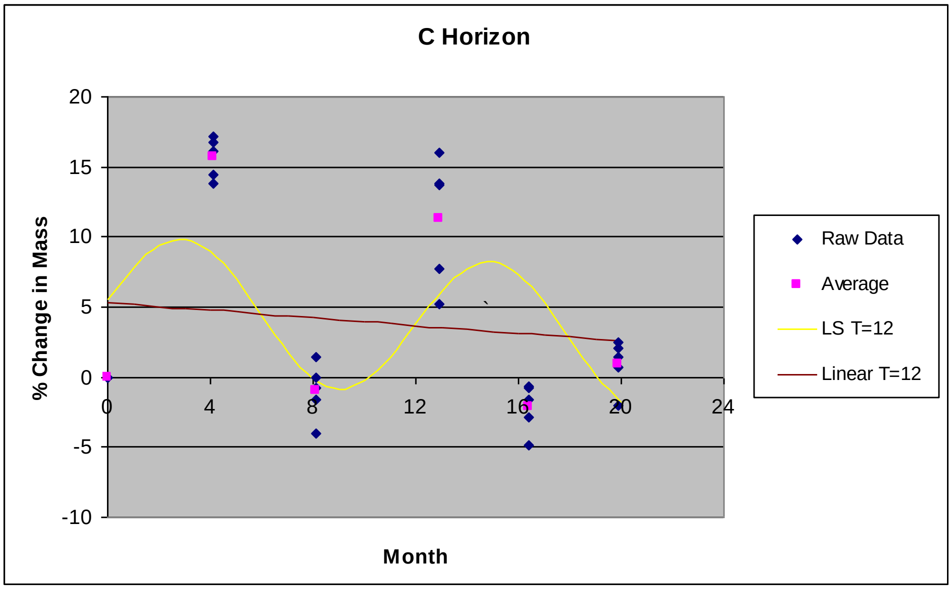


Figure 33: Percent change in mass versus month for C horizon disks with harmonic regression, T = 12 months

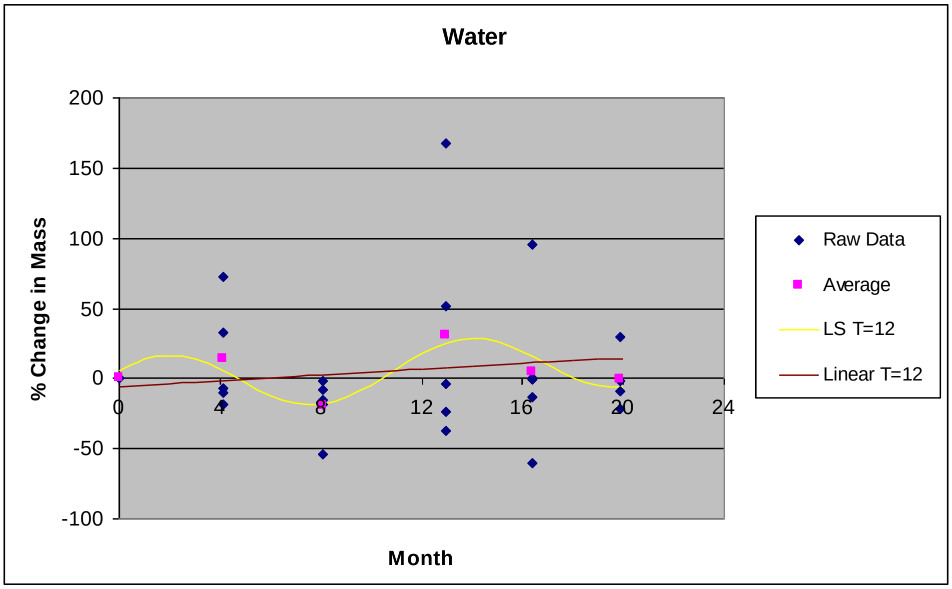


Figure 34: Percent change in mass versus month for submerged disks with harmonic regression, T = 12 months

The constants determined from the least squares analysis for the above plots are summarized in Table 3 for the equation below.

$$y = a_0 + a_1 t + a_2 \sin(2\pi t / T + \phi)$$

	Horizon				
	O	A	B	C	Water
a_0	2.81	-2.22	3.92	5.32	-6.13
a_1	-1.09	-0.04	-0.13	-0.14	1.03
a_2	7.48	12.82	5.12	4.94	20.45
φ	0.25	0.40	0.46	0.03	0.62
T	12.00	12.00	12.00	12.00	12.00

Table 3: Constants from least squares analysis of harmonic regression

Similar to the previous two methods for analyzing the data, the decay rate of the equation (a_1 term) is on average one order of magnitude greater for the disks on the surface (O horizon) compared to the disks that were buried (A, B, and C horizons). Similarly, the disks submerged in water exhibited a positive rate of mass change, which can be related to several sources of error that are discussed later in this section.

While the period has been forced to twelve months to fit a yearly seasonal cycle, the overall fit of the curves appears worse than the least squares curves. This is particularly evident in the B horizon where the least squares curve with the optimal period is very close to the average for each set of data points at the four month intervals. However, for the least squares curve with a period set to twelve months, the curve under-predicts all of the data points for the fourth and twelfth months, while over-predicting in months eight and sixteen. Thus, while the third set of plots fixes the period at twelve months, the curves do not fit the data as well as the curves with optimal periods.

The rate of decay of the disks on the surface was always one order of magnitude greater than the disks buried in the ground. This result was consistent across all three analyses. Tables 4 – 6 summarize the decay rate for each analysis method and present the amount of time it would take, in years, for e-folding to occur given the observed decay rates. The term e-folding refers to the amount of time for 63.2% decomposition, which is based on exponential decay and is found by taking the inverse of the decay rate.

Horizon	Decay Rate (%/month)	e-Folding Time (Years)
O	1.3	6.4
A	0.5	17.2
B	0.3	26.0
C	0.2	35.3

Table 4: Decay rate and e-folding time found using linear regression

Horizon	Decay Rate (%/month)	e-Folding Time (Years)
O	1.3	6.3
A	0.2	42.9
B	0.4	19.8
C	0.4	22.0

Table 5: Decay rate and e-folding time found using least squares, optimal period

Horizon	Decay Rate (%/month)	e-Folding Time (Years)
O	1.1	7.7
A	0.04	208.1
B	0.1	63.5
C	0.1	60.7

Table 6: Decay rate and e-folding time found using least squares, *T* = 12 months

Based on Tables 4 – 6, the wood disks on the surface would take an average of 6.8 years for e-folding decomposition to occur, while the disks buried would take an average of 55 years. While these predictions are only applicable to the wood disks we buried, they give a possible timeframe for the decomposition of entire logs if this carbon sequestration scheme was utilized on a larger scale. A graphical representation of Table 6 can be seen in Figure 35.

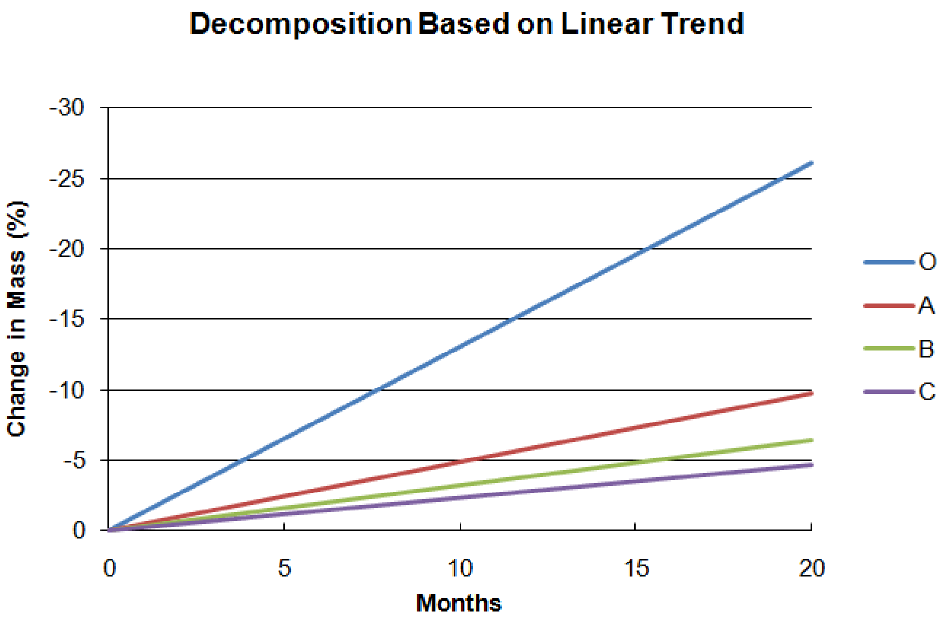


Figure 35: Linear decomposition trends superimposed at origin for all soil horizons

In Figure 35 the linear trend lines found earlier in the analysis are superimposed at the origin. This figure graphically shows the change in mass for each soil horizon over the duration of the experiment. The O horizon (disks placed on the surface of the soil) had a much larger decay rate and smaller e-folding time period, and consequently has the largest slope and corresponding percent change in mass over time. However, the A, B, and C horizons exhibited a smaller decay rate and larger e-folding time period, and the figure shows that these three horizons had a smaller percent change in mass over time compared to the disks placed on the surface (O horizon).

The previous three methods of analysis (linear, harmonic optimal period, and harmonic fixed twelve month period) are based on three mathematical models. However, given that this experiment is based in the field there is inevitably some error between the mathematical models and the observed data. This is particularly evident in the harmonic model with a fixed twelve month period where the model at many places under- or over-predicts the groups of data. To account for the error between the models and the observed data, several factors have been identified as potential sources of variability. One factor is the precipitation that occurred throughout the experiment duration. Different levels of rain and snowfall between seasons would lead to non-uniform trends in decomposition. The effects of precipitation are discussed in a later section. The second factor is the composition of the soil horizons. This factor is also discussed in a later section.

6.1.2 Statistical Significance of Decay Rates

While the raw data suggests that the deeper the disks were interred, the lower the rate of decomposition, it is also important to know to what statistical significance this claim is valid. To determine the statistical significance, 95% confidence interval values were determined for the slope (decay rate) of the linear regression model presented in the preceding section. These confidence intervals are shown in Figure 36.

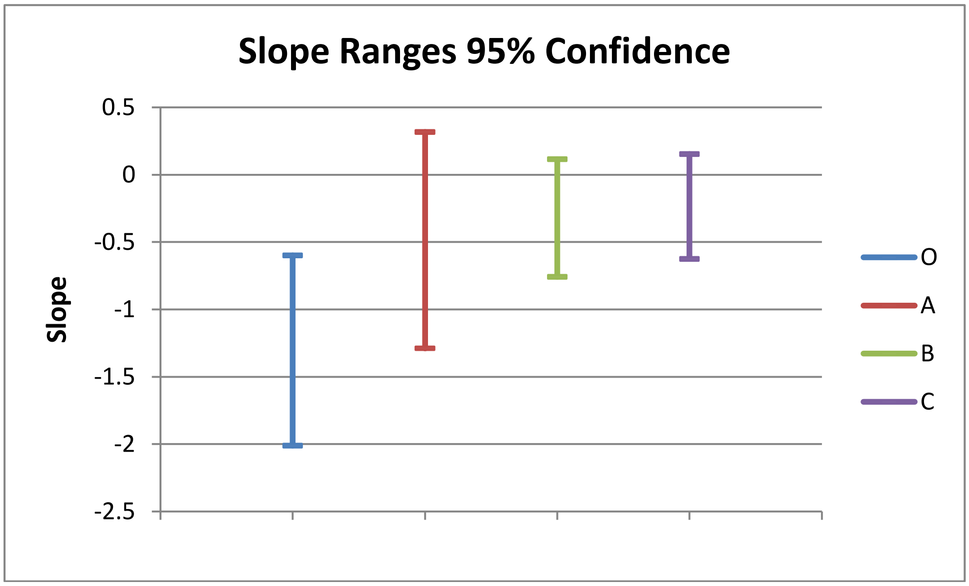


Figure 36: 95% confidence ranges for decay rates

Figure 36 shows that the decay rate for the disks that were interred in the ground (Horizons A, B, and C) is not statistically significant within 95% compared to the disks on the surface (Horizon O); this is shown by overlapped ranges in the confidence intervals for the slope. Furthermore, it can also be noted that all of the disks placed below ground have the potential for slope values that could be greater than zero within this 95% confidence interval. Since during the course of decomposition mass is lost, any slope greater than zero would not be possible. Given the relatively small sample size of the data, it is not unexpected that the data would not be statistically significant within a 95% confidence range. The question that arises is to what statistical significance are the decay rates in the linear model.

We examined several different confidence intervals with the result that the decay rates are significant within a 75% confidence interval. The ranges of the decay rates for this confidence level are presented in Figure 37 below.

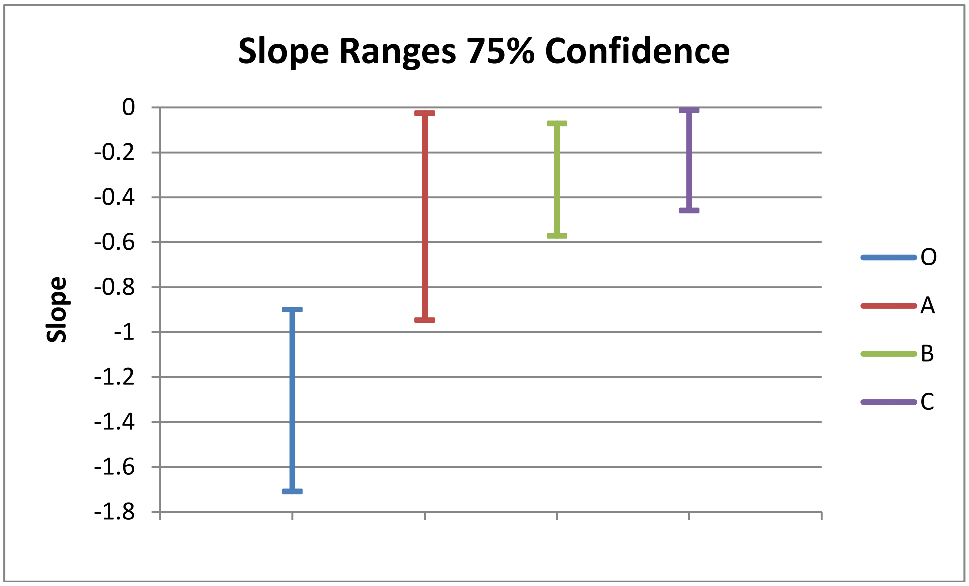


Figure 37: 75% confidence ranges for decay rates

In Figure 37, all of the decay rates for the disks buried in the ground (A, B, and C horizons) now have ranges that are below zero, which fit the intuitive requirement that the decay rate will be negative for decomposition of biomass. In addition, with the exception of the A horizon, the B and C horizons do not overlap with the O horizon (disks on the surface). This means that within 75% confidence, the disks buried in the B and C horizons (the two deepest horizons) would have a smaller decay rate compared to the disks placed on the surface.

6.1.3 Effects of Precipitation and Temperature on Decomposition

The raw data of the change in mass versus time exhibited a cyclic, harmonic pattern. Several factors were analyzed as possible causes of this harmonic pattern. These factors included precipitation and temperature as well as the Standard Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI). The SPI is an index tabulated by NOAA, which measures the drought level using only precipitation. The PDSI is a more complex drought index tabulated by NOAA which takes into account temperature, precipitation, and the area of the country where the index is tabulated. Plots for both temperature and precipitation versus the change in mass are plotted in Figure 38. Note that the change in mass is only plotted for the month where the disks were uncovered in the field, while the temperature and precipitation have been included for all months.

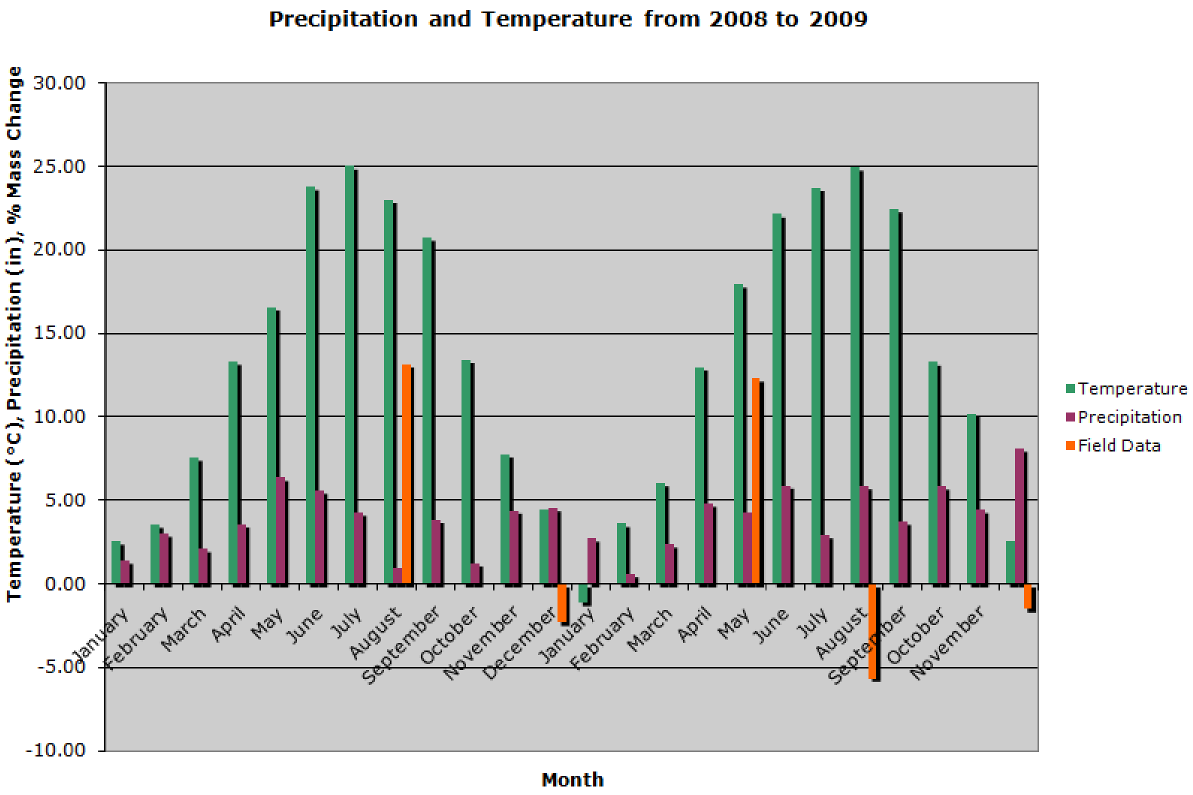


Figure 38: Precipitation, temperature, and percent change in mass versus time

To determine a correlation between temperature, precipitation, SPI, and PDSI with the change in mass of the wood disks, correlation coefficients were calculated. The results of these correlation coefficients are summarized below in Table 7.

Variable	Correlation Coefficient
Temperature	-0.37
Precipitation	0.72
SPI	0.83
PDSI	0.47

Table 7: Correlation between temperature, precipitation, SPI, PDSI, and change in mass

In Table 7, a positive correlation coefficient indicates that as the particular variable increases in value, the magnitude of the percent change in mass increases in the wood disks. From the above table it is evident that an increase in precipitation, SPI, and PDSI indices and a decrease in temperature were correlated with an increase in the decomposition of the wood disks. Looking at the magnitude of the correlation coefficients, it is evident that both temperature and PDSI have the least correlation. PDSI is calculated using temperature data as one of its parameters, so it is expected that the PDSI would follow the same trend as the temperature. However, given the relatively low magnitude of the correlation coefficient, the data suggests that temperature and the PDSI did not have as great of an effect on the data compared to precipitation and the SPI.

Both the precipitation and SPI variables have higher magnitude correlations than temperature and PDSI. These variables are related in that the SPI is calculated using precipitation data in combination with several other factors. The relatively high magnitude of the correlation coefficients for these variables indicates that the precipitation that occurs in the months prior to when the disks are uncovered affects the decomposition of the wood disks. During periods of heavy precipitation, the disks may have decomposed more and have an associated larger decrease in their percent change in mass. This correlation also provides an insight into the possible cause of the harmonic cycle present in the data since variations in the precipitation would affect the decomposition of the wood disks.

6.1.4 Soil Horizon Composition and Effect on Data

As explained previously, soil samples were taken from each horizon in the field during each sample extraction. Through the team's relationship with WREC, the soil samples were sent to A&L Laboratories for routine soil analysis, the completed results of which are included in Appendix III. Such analysis is typically used to determine the availability of nutrients that foster plant growth in the tested soil (Espinoza et al., 2008).

Table 8 below displays the nutrient rate analysis, ranging from Very Low (VL) to Very High (VH), of each element.

Horizon	Date	Organic Matter	Phosphorus: Mehlich 3	Potassium	Magnesium	Calcium
		Rate	Rate	Rate	Rate	Rate
A	8/2008	L	H	L	M	L
A	8/2009	L	M	VL	M	M
A	12/2008	L	H	VL	M	M
A	12/2009	L	H	VH	M	L
B	8/2008	L	M	VL	M	L
B	8/2009	VL	M	VL	H	L
B	12/2008	VL	M	VL	H	L
B	12/2009	VL	VL	L	H	L
C	8/2008	VL	VL	VL	M	L
C	8/2009	VL	M	VL	H	L
C	12/2008	VL	M	VL	H	VL
C	12/2009	VL	L	L	H	L

Table 8: Soil chemistry by horizon and date

Initial observation shows a clear chemical distinction between the horizons, particularly between horizons A and C. The high levels of Phosphorous: Mehlich 3 in the A stratum suggests that this portion of soil may have been fertilized in the past and would therefore encourage plant growth at this level. This phosphorous content along with overall medium magnesium and calcium levels makes this stratum hospitable to plant growth. This was observed in the field as well, the wood samples left on the surface as well as those in soil horizon A were often found with plants and roots growing around and through the sample.

6.1.5 Potential Sources of Error

Several sources of error have been identified that may have affected the results collected throughout the field experiment. The foremost of these errors was the failure to completely dry the wood disks after they were uncovered. This error probably had the most effect on the disks submerged in water. The second error source was the comparatively short length of the field experiment and its relation to the mathematical models chosen.

We dried the disks for three days in an oven at 150° C. This time period was selected based on the first group of disks uncovered after four months into the experiment. Drying of these disks was monitored and the mass stabilized after three days of drying. However, some data points in subsequent months showed a positive change in mass. The cause of this error was probably due to water that had been trapped deep in the cell structure of the wood disks that had not evaporated after three days. This effect was exacerbated in the case of the submerged wood disks, where the water would have ample time to completely saturate the wood and penetrate deep into the cell structure of the disks. As a result, the wood disks submerged in water exhibited a positive change in mass.

A similar potential source of error is that the wood disks in the experiment that had more mass would retain more water during the drying process, which could skew the results. To test this, the initial mass of the disk was compared to how the percent mass change for that disk deviated from the average for all the disks uncovered during that month. The expectation is that disks with larger mass would have percent mass change that would deviate above the average percent mass change for the month it was uncovered, which could signify that drying may have been incomplete in these larger wood disks. The initial mass has been plotted compared to the percent mass change deviation from the average in Figure 39 below for all of the data points.

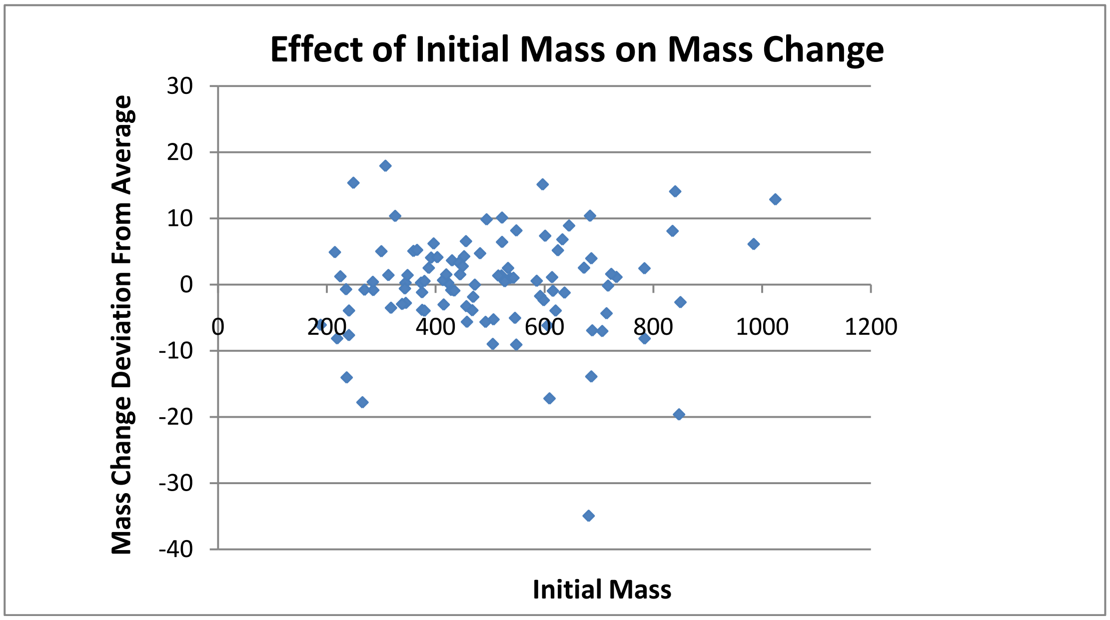


Figure 39: Effect of initial mass on mass change for all data points

Based on Figure 39, there does not appear to be an observable correlation within the data. Indeed, the correlation coefficient between the initial mass and the mass change deviation from the average yielded a value of 0.02, which shows that there is almost no correlation between these variables across all of the data points. However, the plot in Figure 39 was created using all of the data points during the course of the experiment, but on closer inspection of how the data changed every four months, it becomes apparent that the months with the largest positive increase in mass and largest amount of precipitation occurred around months 4 and 12 (see initial plots in Section 6.1.1). Thus, it may be possible that during the drier months there may have been more comprehensive drying compared to months 4 and 12 where there was more precipitation prior to uncovering the disks. If this were the case, there may be a correlation between the wood disk size and the deviation from the average change in mass for these two months only (months 4 and 12). The initial mass plotted against the percent mass change deviation for only these two months is presented in Figure 40 below.

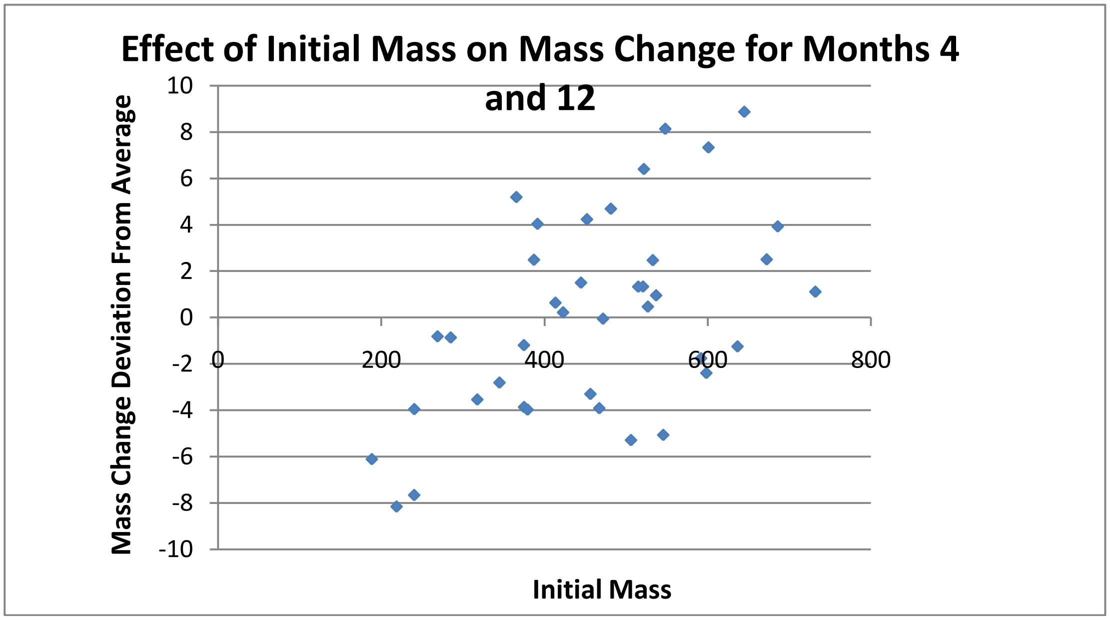


Figure 40: Effect of initial mass on mass change for months 4 and 12

From Figure 40 it is evident that there is some trend between the variables for these two months. A correlation coefficient between the two variables yields a value of 0.53, which is much larger than the coefficient of 0.02 that was found for all of the data points. What this shows is that for the wetter months with more precipitation prior to uncovering the disks (months 4 and 12), the disks with larger mass had deviated above the average mass for that month. This suggests that the wood disks with larger mass may have absorbed more water and subsequently may have had incomplete drying before their final masses were measured.

The second major source of error in the mathematical models' fit to the raw data was the length of the experiment. Due to time limitations, the experiment was run for twenty months. As described above, seasonal trends were observed in the data and a harmonic model was chosen to fit the data. Using least squares regression, the various constants of the harmonic model were optimized, however, the period term in the model showed some variability and the optimal period was typically between nine and ten months. The expected period based on intuition was twelve months to correspond to an annual seasonal cycle. Since the experiment was performed over twenty months, the period term in the harmonic model was heavily influenced by this short experiment span. It is possible that with several more years of data the period term in the harmonic model may have converged on a twelve month period. Thus, the length of the experiment was a large factor in affecting the period constant in the harmonic models and was the basis for performing a linear regression in addition to the harmonic models to analyze the data.

6.2 Lab Experiment Results and Analysis

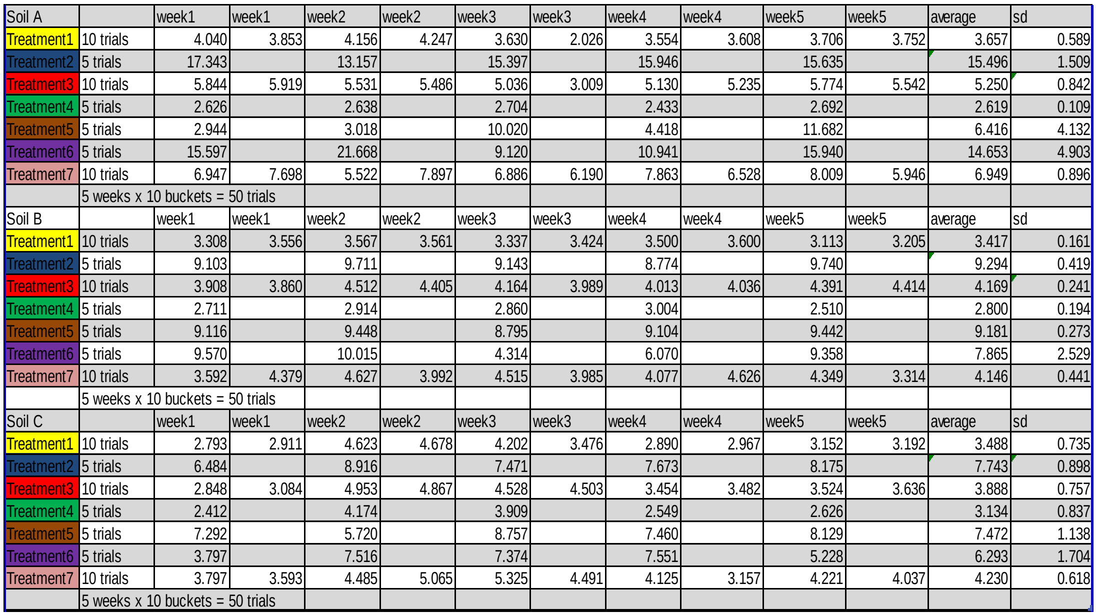
We started the laboratory portion of our project in March 2009 in Dr. Bruce James' soil lab. The first month or so was spent perfecting our methodology by testing different run-times. Trials were run for between three and 14 days. We also ran several trials in order to determine the optimal drying time needed to get rid of any weight gain due to water. From these initial trials, we found that one week was the optimal time, both for experimental run-time and for baking the soda lime.

After running five one-week trials for each of the soil types (horizons A, B, and C), we compiled our results. Before any analysis was run, we organized the data in two ways, by percent mass change and by a standardized difference in mass change of the soda lime. Percent change was found by dividing the change in mass of the soda lime after drying by the mass of the soda lime before it was placed in the buckets. The standardized difference was found by dividing the change in mass (mass after drying – initial mass) by the initial mass of the soda lime and the beaker. See Table 9 below for an example percent change and standardized difference.

Horizon B				
WEEK 1	7/8/2009			
	Initial Mass	Final Mass	%Change	st. diff.
Bucket 1	65.753	66.22	3.308	0.007
Bucket 2	60.478	60.976	3.556	0.008
Bucket 3	66.403	67.677	9.103	0.019
Bucket 4	64.165	64.715	3.908	0.009
Bucket 5	63.85	64.391	3.860	0.008
Bucket 6	63.387	63.767	2.711	0.006
Bucket 7	62.406	63.682	9.116	0.020
Bucket 8	63.8	65.14	9.570	0.021
Bucket 9	62.159	62.663	3.592	0.008
Bucket 10	63.069	63.684	4.379	0.010

Table 9: Example of two different measurements for horizon B, week 1

Initially, we thought that standardized difference might be a better measurement than percent change because percent change is more affected by the initial mass of the soda lime. However, both measurements were analyzed with the Analysis of Variance (ANOVA) and both yielded the same results. We chose to use only percent change because we felt it was more intuitive.



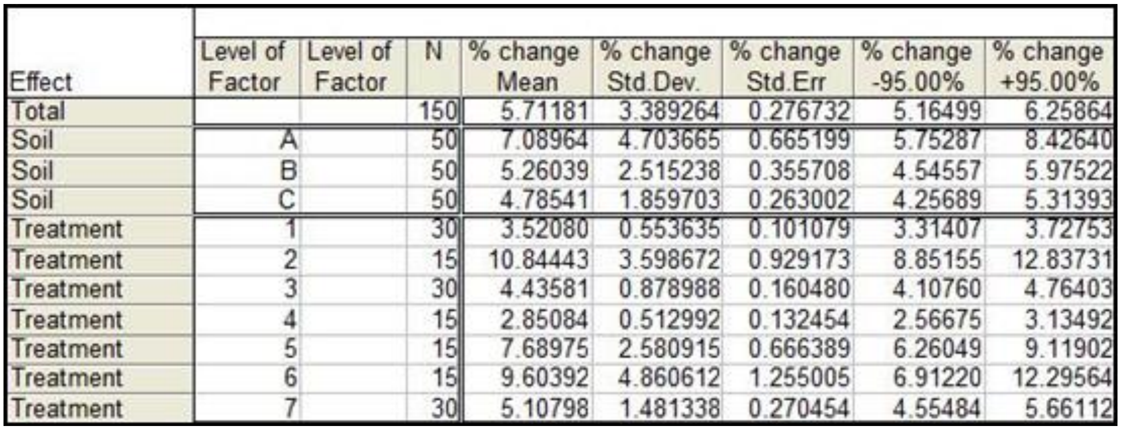
Soil A		week1	week1	week2	week2	week3	week3	week4	week4	week5	week5	average	sd
Treatment1	10 trials	4.040	3.853	4.156	4.247	3.630	2.026	3.554	3.608	3.706	3.752	3.657	0.589
Treatment2	5 trials	17.343		13.157		15.397		15.946		15.635		15.496	1.509
Treatment3	10 trials	5.844	5.919	5.531	5.486	5.036	3.009	5.130	5.235	5.774	5.542	5.250	0.842
Treatment4	5 trials	2.626		2.638		2.704		2.433		2.692		2.619	0.109
Treatment5	5 trials	2.944		3.018		10.020		4.418		11.682		6.416	4.132
Treatment6	5 trials	15.597		21.668		9.120		10.941		15.940		14.653	4.903
Treatment7	10 trials	6.947	7.698	5.522	7.897	6.886	6.190	7.863	6.528	8.009	5.946	6.949	0.896
	5 weeks x 10 buckets = 50 trials												
Soil B		week1	week1	week2	week2	week3	week3	week4	week4	week5	week5	average	sd
Treatment1	10 trials	3.308	3.556	3.567	3.561	3.337	3.424	3.500	3.600	3.113	3.205	3.417	0.161
Treatment2	5 trials	9.103		9.711		9.143		8.774		9.740		9.294	0.419
Treatment3	10 trials	3.908	3.860	4.512	4.405	4.164	3.989	4.013	4.036	4.391	4.414	4.169	0.241
Treatment4	5 trials	2.711		2.914		2.860		3.004		2.510		2.800	0.194
Treatment5	5 trials	9.116		9.448		8.795		9.104		9.442		9.181	0.273
Treatment6	5 trials	9.570		10.015		4.314		6.070		9.358		7.865	2.529
Treatment7	10 trials	3.592	4.379	4.627	3.992	4.515	3.985	4.077	4.626	4.349	3.314	4.146	0.441
	5 weeks x 10 buckets = 50 trials												
Soil C		week1	week1	week2	week2	week3	week3	week4	week4	week5	week5	average	sd
Treatment1	10 trials	2.793	2.911	4.623	4.678	4.202	3.476	2.890	2.967	3.152	3.192	3.488	0.735
Treatment2	5 trials	6.484		8.916		7.471		7.673		8.175		7.743	0.898
Treatment3	10 trials	2.848	3.084	4.953	4.867	4.528	4.503	3.454	3.482	3.524	3.636	3.888	0.757
Treatment4	5 trials	2.412		4.174		3.909		2.549		2.626		3.134	0.837
Treatment5	5 trials	7.292		5.720		8.757		7.460		8.129		7.472	1.138
Treatment6	5 trials	3.797		7.516		7.374		7.551		5.228		6.293	1.704
Treatment7	10 trials	3.797	3.593	4.485	5.065	5.325	4.491	4.125	3.157	4.221	4.037	4.230	0.618
	5 weeks x 10 buckets = 50 trials												

Table 10: Raw data for percent change in mass of soda lime for all soil types and all treatments

Because of the controlled laboratory environment and because every week, for each soil horizon, we reset the buckets exactly as they were the previous week, each week was treated as an individual trial. This means that over the five week test period for each soil horizon, there were 50 total trials for the soil type and at least five trials per treatment. As shown in Table 10 (above), Treatments 1, 3, 7 each had ten trials because there were two buckets for each every week.

Also, it is important to note that the percent change in mass of soda lime is directly proportional to the amount of carbon dioxide which the soda lime absorbs. Thus the percent change in mass of soda lime can be used as a relative measure for the amount of carbon dioxide released through respiration of soil microbes. However, until the data were analyzed, it was impossible to determine how much of the carbon dioxide released was due to background soil respiration and how much was due to respiration from the decomposition of the sawdust.

6.2.1 General Trends in Raw Data



Effect	Level of Factor	Level of Factor	N	% change Mean	% change Std.Dev.	% change Std.Err	% change -95.00%	% change +95.00%
Total			150	5.71181	3.389264	0.276732	5.16499	6.25864
Soil	A		50	7.08964	4.703665	0.665199	5.75287	8.42640
Soil	B		50	5.26039	2.515238	0.355708	4.54557	5.97522
Soil	C		50	4.78541	1.859703	0.263002	4.25689	5.31393
Treatment	1		30	3.52080	0.553635	0.101079	3.31407	3.72753
Treatment	2		15	10.84443	3.598672	0.929173	8.85155	12.83731
Treatment	3		30	4.43581	0.878988	0.160480	4.10760	4.76403
Treatment	4		15	2.85084	0.512992	0.132454	2.56675	3.13492
Treatment	5		15	7.68975	2.580915	0.666389	6.26049	9.11902
Treatment	6		15	9.60392	4.860612	1.255005	6.91220	12.29564
Treatment	7		30	5.10798	1.481338	0.270454	4.55484	5.66112

Table 11: Means and standard deviations of percent change in mass of soda lime for each soil horizon, treatment

Although no definite conclusion could be drawn until after the ANOVA was run, there were several apparent trends in the raw data. The most obvious trend was that soil horizon did appear to affect the magnitude of percent change in mass of soda lime. As shown in Table 11 and Figure 41, soil from horizon A showed the greatest average (7.1%) and total percent change, while soil from horizon C showed the least average (4.8%) and total percent change. Because horizon A is closest to the surface and horizon C furthest down, it can be inferred that deeper soils release less carbon dioxide than those closer to the surface.

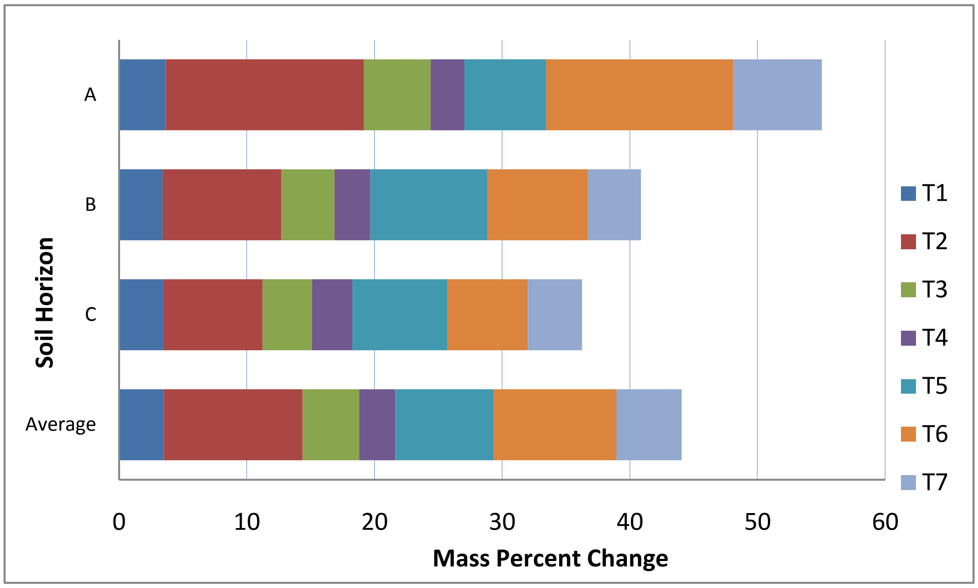
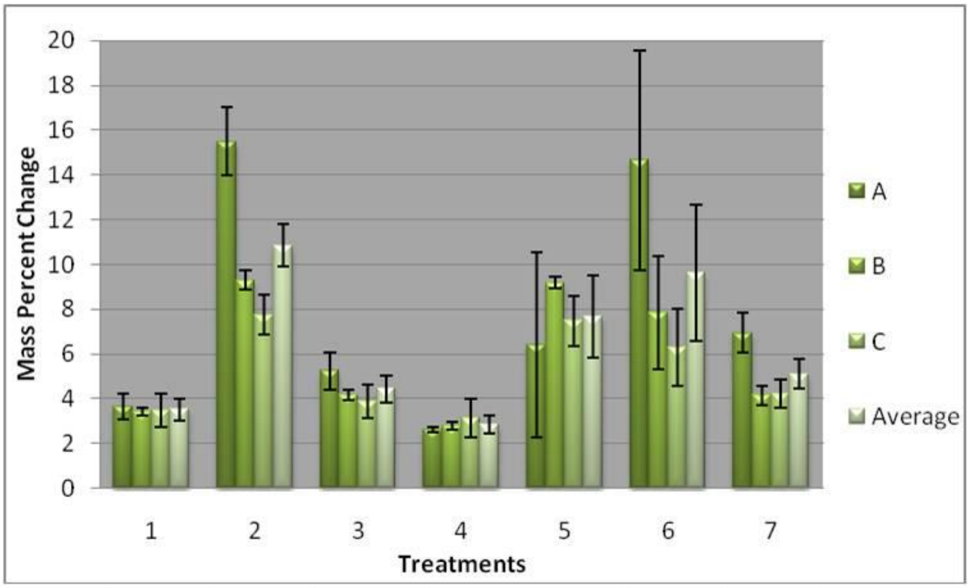


Figure 41: Comparison of total percent change in mass of soda lime over all treatments by soil horizon

The other trend which can be observed in the raw data is that the different variables did appear to affect the magnitude of percent change in mass of soda lime. Treatment 2, the room temperature fertilizer treatment, had the highest average percent change (10.8%), and Treatment 4, which we will hereafter refer to as the 'soil control', had the lowest average percent change (2.9%) (Table 11).When compared to Treatment 3, which we will hereafter refer to as the 'natural control', all three of the fertilizer treatments (Treatments 2, 5, and 6) showed increased percent change. Figure 42 shows that the incubated treatment, Treatment 7, showed a lesser increase in percent change, and the flooded treatment, Treatment 1, showed a decreased percent change.

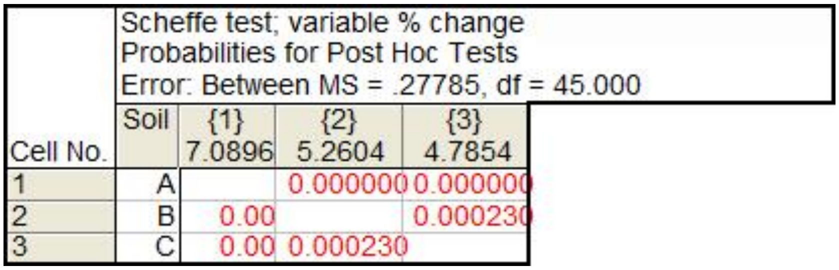


	1	2	3	4	5	6	7
Soil	X	X	X	X	X	X	X
Sawdust	X	X	X			X	X
Fertilizer		X			X	X	
Flooded	X						
Incubated						X	X

Figure 42: Percent change in mass of soda lime by treatment; Standard deviation represented by error bars

6.2.2 Analysis of Data

After we ran the ANOVA on our data, it was found that there was a statistically significant difference between each of the three soil horizons with a confidence of 99.95%; this is shown in Table 12 and Figure 43. There was also a statistically significant difference, within 99%, between each of the seven treatments, as shown in Table 13 and Figure 44. This means that the trends we observed in the raw data reflect an actual trend in our experiment.



Scheffe test; variable % change
Probabilities for Post Hoc Tests
Error: Between MS = .27785, df = 45.000

Cell No.	Soil	{1} 7.0896	{2} 5.2604	{3} 4.7854
1	A		0.000000	0.000000
2	B	0.00		0.000230
3	C	0.00	0.000230	

Table 12: Analysis of means of the three soil horizons

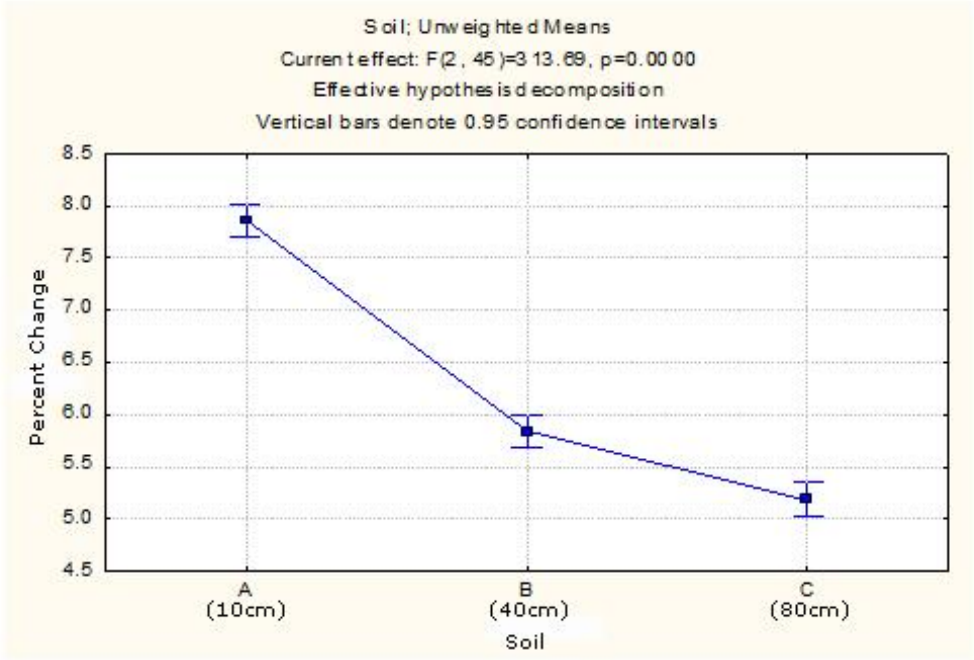
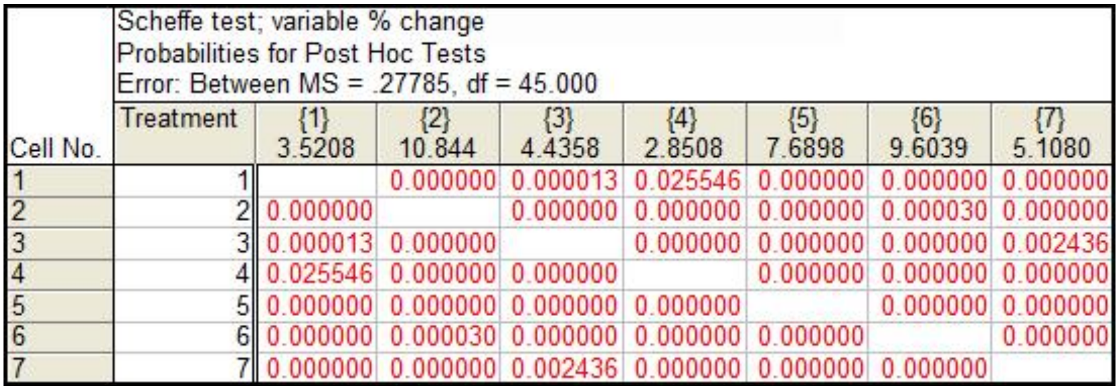


Figure 43: Graphical representation of percent change in mass of soda lime for each soil horizon



Scheffe test; variable % change
Probabilities for Post Hoc Tests
Error: Between MS = .27785, df = 45.000

Cell No.	Treatment	{1} 3.5208	{2} 10.844	{3} 4.4358	{4} 2.8508	{5} 7.6898	{6} 9.6039	{7} 5.1080
1	1		0.000000	0.000013	0.025546	0.000000	0.000000	0.000000
2	2	0.000000		0.000000	0.000000	0.000000	0.000030	0.000000
3	3	0.000013	0.000000		0.000000	0.000000	0.000000	0.002436
4	4	0.025546	0.000000	0.000000		0.000000	0.000000	0.000000
5	5	0.000000	0.000000	0.000000	0.000000		0.000000	0.000000
6	6	0.000000	0.000030	0.000000	0.000000	0.000000		0.000000
7	7	0.000000	0.000000	0.002436	0.000000	0.000000	0.000000	

Table 13: Analysis of means of the seven treatments

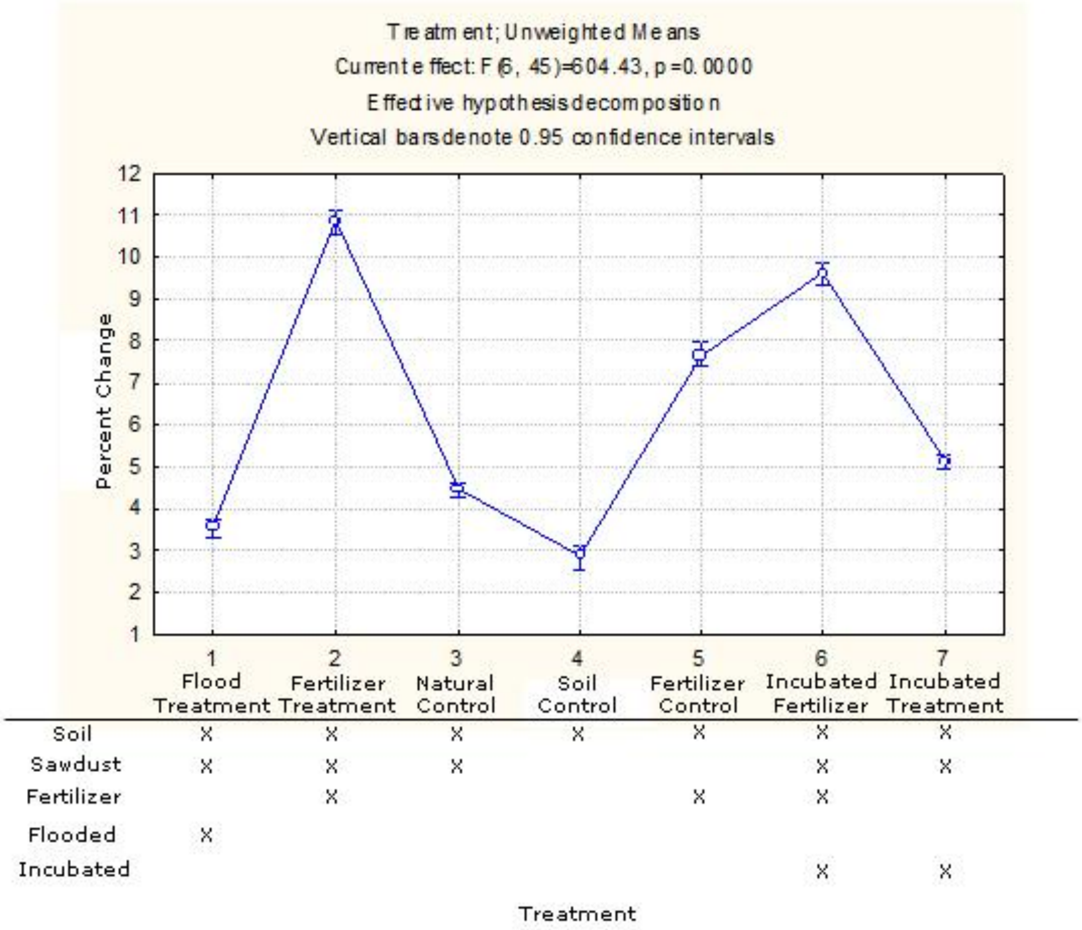


Figure 44: Graphical representation of percent change in mass of soda lime for each treatment

However, before further conclusions could be drawn, we had to determine if and to what extent the decomposition of the sawdust was contributing to the amount of CO_2 absorbed by the soda lime. This was accomplished first by comparing the natural control, which contained soil and sawdust, to the soil control, which contained only soil. Since there was a statistically significant difference between the means of the two treatments (4.44% for the natural control compared to 2.85% for the soil control), we concluded that at least some of the percent change in soda lime mass is attributable to decomposition of sawdust. The extent to which the CO_2 released through the decomposition process contributes to the total percent change can be found by subtracting the soil control mean percent change from the natural control mean percent, and then by dividing that number by the natural control mean percent change ((4.44% - 2.85%)/4.44%). The result is that 36% of the CO_2 absorbed by the soda lime is due decomposition of sawdust. Although this initially seems low, it is actually a significant portion. This is because the mass of the sawdust contributes less than 5% to the total mass of the bucket.

The same process was applied to Treatment 2, the room temperature fertilizer treatment, and Treatment 5, the fertilizer control. The result was that 30% of the carbon dioxide absorbed by the soda lime is due decomposition of sawdust. The difference between the extent to which the decomposition of sawdust affects the total carbon dioxide absorbed in natural control and in the fertilizer treatment is likely due to the fertilizer itself releasing some CO_2.

After confirming that a significant portion of the percent change in soda lime mass is due to the decomposition of the sawdust and not solely due to background soil respiration, conclusions were made about the degree to which each soil horizon and each variable affects decomposition. First, the mean percent change for each soil horizon was correlated with the depth from which it was taken. Soil from horizon A, the highest horizon, allowed the greatest decomposition. Soil from horizon B, the intermediate depth, allowed less decomposition than horizon A but more than horizon C. Soil from horizon C, the lowest depth, allowed the least decomposition. From this trend, it can be inferred that the deeper the wood is buried, the more decomposition will be inhibited.

The analyzed results show that all three variables tested affected the rate of decomposition. Because the fertilizer treatments, including the fertilizer control, had the three highest mean percent changes, it can be concluded that the addition of nutrients, specifically of 6g of fertilizer, had the greatest impact on decomposition and greatly increased decomposition. The flooded treatment, Treatment 1, allowed almost 21% less decomposition than the natural control, so it can be concluded that flooding significantly inhibits decomposition. Lastly, the incubated treatment, Treatment 7, allowed about 15% more decomposition than the natural control, so it can be concluded that increasing the temperature from 25°C to 35°C increases decomposition, but not nearly as much as the addition of 6g of fertilizer as displayed in Figure 45.

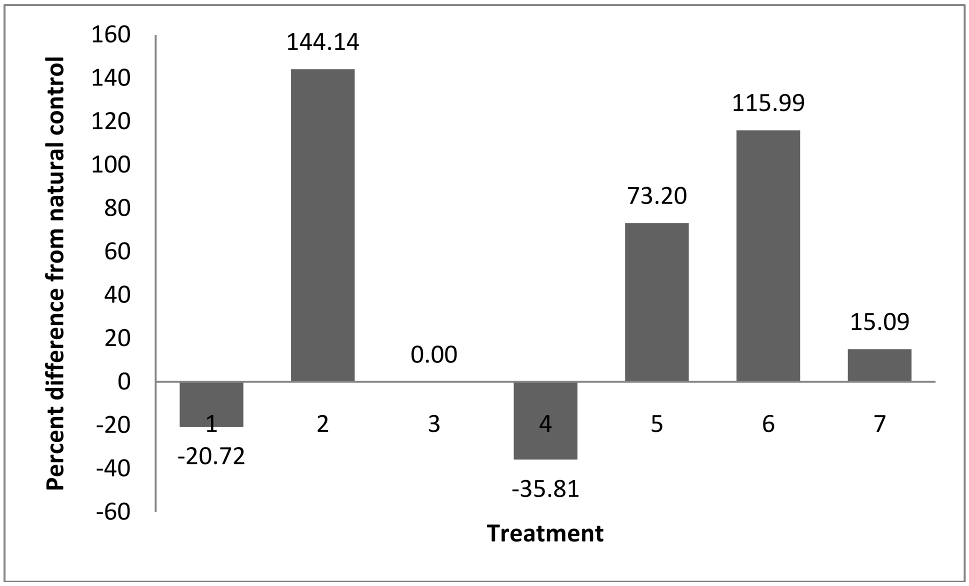


Figure 45: Percent that each treatment differed from the natural control

6.2.3 Implications to Field Research

Our lab experiment allowed us to draw conclusions about the relative degree to which each soil type and each variable (water saturation, addition of nutrients, and increased temperature) affected decomposition of sawdust in a controlled environment. From our results, we are able to make inferences about general trends and determine what conditions should be examined in future field studies. Although it is tempting to make inferences about the relative importance of each variable, we cannot make any definite conclusion about which is actually more important, because the amounts/units of each variable are not equivalent. It is impossible to determine how much fertilizer is equivalent to flooding with 200ml of water or what increase in temperature is equivalent to 6g of fertilizer.

However, based on our findings, we can make suggestions about the ‘optimal’ environment in which to bury wood in order to most inhibit decomposition. Our first suggestion is to bury the wood as deep as possible. Because horizon C, which allowed the least decomposition, is mostly clay, burying the wood at or below 80cm would ensure that the soil composition is similar to that of soil in horizon C. This would allow the least decomposition. Our second suggestion would be to bury the wood in saturated soil or below the water table because the flooded treatment inhibited decomposition. This suggestion is not mutually exclusive with our first suggestion because the deeper the wood is buried, the more likely it will be below the water table. Along with our first two suggestions, burying the wood in a cooler area would also inhibit decomposition. This is based on our findings that increased temperature increases decomposition. This is also related to burying the wood as deep as possible, because the deepest horizon is also the coolest. Our last suggestion would be to find an area with low nutrient or leached soils in which to bury the wood. This is based on our findings that adding nutrients greatly increased the rate of decomposition.

6.2.4 Limitations of Lab Experiment

Although the variables we tested all significantly affected the decomposition rate of wood, there are several other variables which were not tested which may be as or more important. Factors such as pH and oxygen content vary at different depths and in different environments and may play a significant role in the decomposition process. Future studies should examine each variable we tested in further detail. Although we found that adding fertilizer increases decomposition, future studies could examine how different levels of specific soil nutrients, such as nitrates and phosphates, affect decomposition. Similarly, further experiments are needed to determine how and to what extent different temperatures and different water contents affect decomposition. Just like our field experiment was a proof of concept experiment, this lab experiment functioned more as a tool to determine what variables to study further in the field, rather than a comprehensive examination of the quantitative effects of the variables tested.

6.3 Computer Modeling Results and Analysis

Figures 46 – 48 each depict 1000 trials of JABOWA-CS simulated 10x10m plots of loblolly forest. Both living tree biomass and dead tree biomass were plotted. Though tree growth is intended to be random, the following simulations were all run with the same random number seed. JABOWA's pseudorandom algorithm resulted in the trees in our simulation growing and dying in a deterministic pattern, allowing a more direct comparison of results.

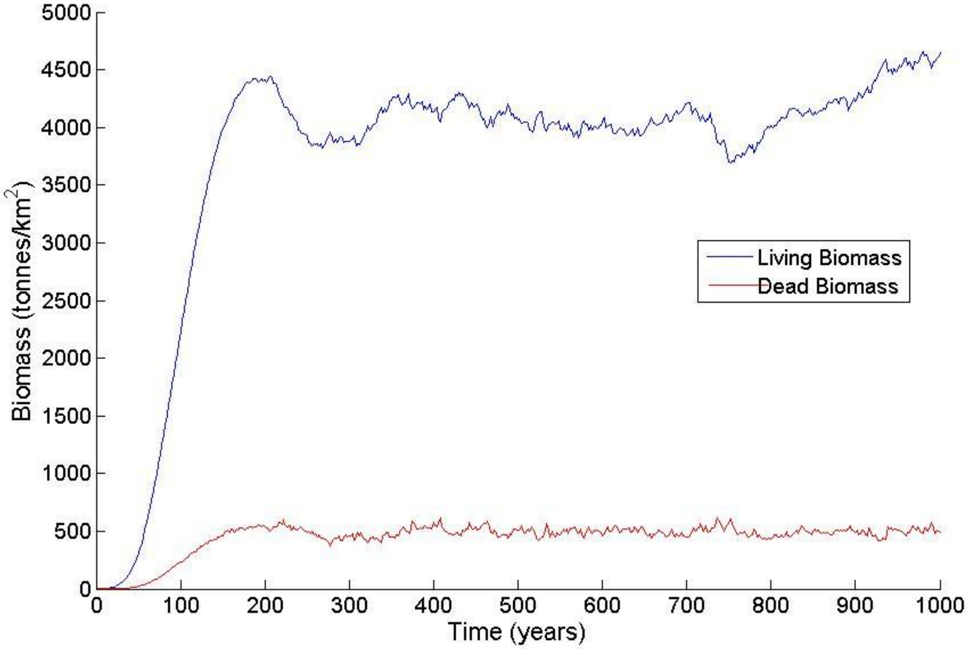


Figure 46: Above ground decay of living and dead biomass at 15.5% per year

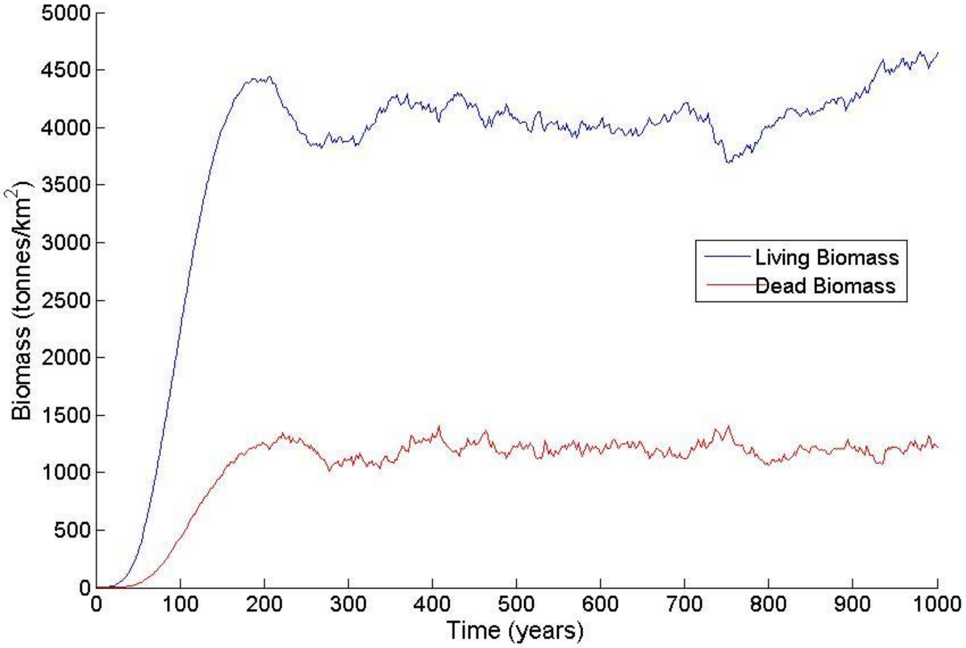


Figure 47: Below ground decay of living and dean biomass at 5.2% per year

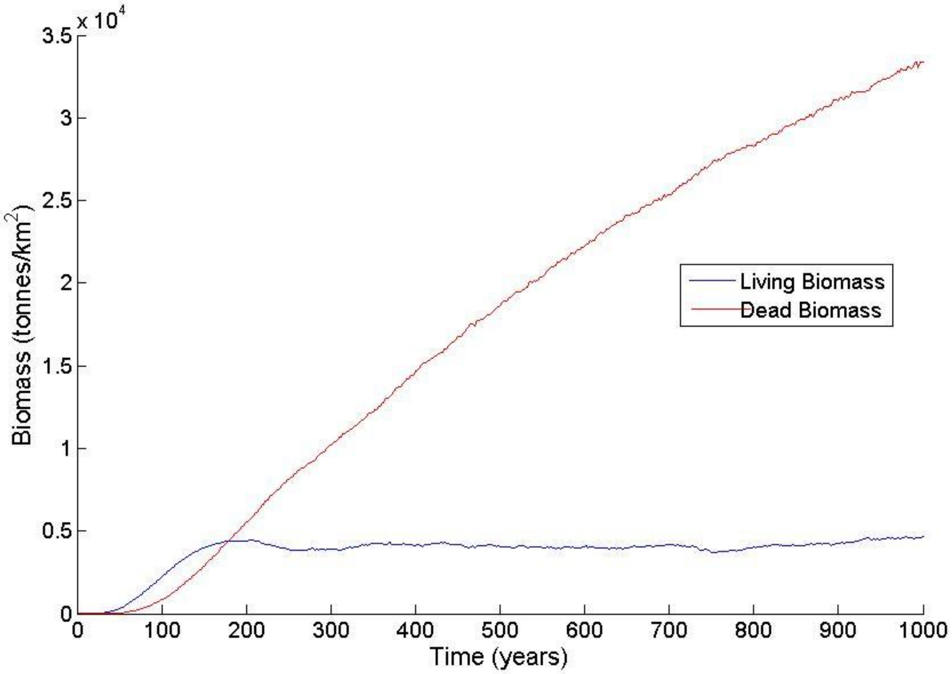


Figure 48: Below ground decay of living and dead biomass at 0.1% per year

6.3.1 Analysis

We found that forests grown from scratch take a certain amount of time to reach equilibrium where the concentration of living trees has peaked. The biomass of the living forest thus undergoes a growth phase taking X number of years, reaching an equilibrium value of Y metric tonnes/km^2. Dead biomass follows a similar pattern, but our independent variable (the decay rate) affects the value of both of these values in our simulation.

Decay rate (%/year)	Time to reach equilibrium (years)	Equilibrium biomass concentration (tonnes/km^2)
15.5	200	400
5.2	220	1200
0.1	>1000	Out of range

Table 14: Summary of modeling data

From the results of our model, a decrease in decay rate from 15.5%/year to 5.2%/year caused an increase in steady-state dead biomass to rise from 400 metric tonnes/km^2 to 1200 tonnes/km^2. These numbers take on more significance when compared to the e-folding decomposition values found from our field data. Both the aboveground and belowground decay rates found from literature corresponds well with the decay rate found in our field study. The 5.2%/year case can then be used to roughly predict the sequestration potential of a full-scale loblolly forest on the eastern shore of Maryland, given that all naturally dying wood were interred as low as the C horizon of soil 0.8 meters down. A threefold decrease in the decay rate results roughly in a threefold increase in the steady-state equilibrium concentration of dead biomass. This suggests that a closely managed loblolly forest in which all naturally dying trees are found and interred at approximately one meter below ground peaks in the amount of benefit offered after the new equilibrium is reached roughly after 200 years. After this time, more money must be spent on burial efforts in order to maintain the raised equilibrium. Otherwise, the forest's stored dead biomass will revert to its natural values.

As the decay rate approaches zero, not only does the equilibrium continue to rise, but the time taken to reach that equilibrium is longer, and in fact is not reached in our simulation time scale of 1000 years. This means that the sequestration method is approaching that of geological sequestration. For every tonne of carbon sequestered, very little leaks back into the environment. This treatment case is meant to predict the potential for forest sequestration if a near-ideal decay prevention mechanism is developed.

The slope of the roughly linear trend of the mass concentration of dead wood in the first 1000 years is 25 tonnes/km^{2}yr. This means that on a millennial time scale, more sequestration value can be obtained, or more carbon emissions can be offset on a carbon market, for every dollar invested in the burial scheme.

6.3.2 Real-world Applicability of Results

Several major assumptions were made in the process of obtaining the simulated results. We assumed that all wood is sequestered automatically upon death, no matter how minor the tree is upon death. This is mitigated by the fact that saplings compose only a small minority of a plot's biomass, where it is usually stored in just a few large trees. We also assumed that all dead biomass is obtained from natural death and not artificial means, such as logging.

Obviously, these assumptions are impractical and ecologically unbalancing. We could seriously disrupt forest ecosystems by burying all dead wood in a natural forest. In addition, on-site burial, while fine for experimental purposes, would probably be a poor way to control costs, especially with respect to large-scale burial of coarse woody debris. Our modeling experiments are meant only to reflect the natural productive capabilities of loblolly forests and analyze the effect of differing decay rates on long-term decay pools.

However, ecological concerns are reduced when we limit our consideration to managed forests such as stands grown for timber purposes. A rough cost-benefit analysis can then be made by comparing the carbon market and the lumber market (see Table 15).

Type of wood	Cut from tree of diameter: (Clatterbuck & Ganus, 1999)	Dollar price per metric tonne: (Fiery, 2010)
Pulpwood	4-7 inches	15.86
Chip-and-Saw	8-11 inches	7.09
Sawtimber	12 inches or more	31.54

Table 15: Quarter 1 of 2010 market prices for pine timber per metric tonne

The above prices reflect the opportunity cost to society of burying wood. The price is the wood's worth to society if it were sold on the lumber market; larger logs are worth more, but it is important to consider that while all parts of the log provide the same carbon value, only parts of it provide full-price lumber value, especially when looking at more valuable types of lumber such as sawtimber.

The benefit to society is captured in the price of carbon allowances on the carbon market. The price for one European Union Allowance (EUA) of CO_2 in April 2010 on the European Union carbon market was €13.97 (European Climate Exchange, 2010). One allowance represents the right to emit one tonne of CO_2. This converts to a value of $34.15 per tonne of loblolly pine on the carbon market, exceeding even that of sawtimber on the US lumber market.

The above analysis assumes an equivalence of one tonne of CO_2 not emitted to an equivalent mass of CO_2 buried underground. This would only be roughly true in the case that the buried woody debris could be demonstrably sequestered at zero decay. In reality, there may be a negative bias toward the price of sequestered carbon versus carbon not emitted, or carbon allowances.

Ultimately, the benefit to society minus the opportunity cost to society equals the cost of sequestering lumber plus any potential profit. Assuming a market for sequestered lumber existed, even as of Quarter 1 of 2010 the margin for lumber sequestration is on the order of $10 per ton. A more detailed economic analysis as well as further progress on a method to limit the decay rate of woody biomass would be necessary to truly determine the cost and benefits of the burial and maintenance of wood in a sequestered state. The first estimate, however, is optimistic.

Chapter 7: Conclusions and Directions for Future Research

7.1 Overall Conclusions

The most readily apparent conclusion that can be drawn from the field data is the difference in decomposition rates between above- and below-ground samples. The above-ground samples, when fitted to a linear or harmonic curve, had a decomposition rate approximately four times higher than those buried 80cm underground. The decomposition rates decreased the further underground the samples were buried. There is no readily apparent process that would cause this difference in decomposition rates, which leads us to attribute this differential decomposition to the burial depth of the sample. It is important to note that extrapolating exact lengths of decomposition from a 20 month experiment is not possible. Woody biomass is composed of both cellulose and lignin, and lignin decomposes much slower than cellulose. This suggests that timescales estimated from our data may be shorter than an actual decomposition timescales, as our data likely results mostly from cellulose decomposition. The magnitude of the difference in decomposition rates between the above- and below-ground samples may also change over time, as the rate of lignin decomposition may be different when buried.

When plotted against time, the field decomposition data produced a set of points that can be fitted with a harmonic curve. This implies a cycle of some sort, but the exact cause is undetermined. The optimum period of this cycle is 9-10 months, which appears to rule out yearly or seasonal variation. This may be misleading, as error and the few points available can cause false variations in the period. A more likely cause is precipitation. Precipitation was positively correlated with a mass above the value expected in a linear model. This suggests that the method of drying the logs employed was insufficient to remove moisture from saturated samples.

In addition to burying disks, wood was also submerged underwater to analyze aquatic sequestration potential. This data proved difficult to analyze and hence was not included in the overall results. In all tests, the mass of the water samples increased from their original mass which suggests that the drying process employed was insufficient, or that some as yet unidentified process was at work in the water samples.

The laboratory portion of the experiment was designed to address the individual factors which impact decay. It was found that higher temperatures and increased access to nutrients, such as nitrogen, caused an increased rate of carbon dioxide evolution, which corresponds to increased decomposition. It was also found that flooding the test chamber with water resulted in a decrease in carbon dioxide evolution. This suggests that limited access to oxygen is a vital component of reducing decomposition activity. Sequestration can be optimized by storing wood below the water table in nutrient-poor soil, or submerged underwater in areas with cool climates.

Computer modeling data were used to determine long-term outcomes of wood burial sequestration at varying rates of decomposition. The modeling data showed that unless decomposition is minimized, sequestration potential reaches a steady state related to the decomposition rate. It is important to note that this steady-state is based on harvesting trees from one forest after they die naturally. In any practical and responsible system, only a small percentage of this amount would be gathered from the forest. It does not show a definite upper limit for sequestration potential, but instead shows that high decomposition rates require wood to be buried each year to maintain the amount of carbon sequestered. It was found that the fourfold decrease in decomposition from 16% to 4% per year reported in the field experiments corresponds to a fourfold increase in sequestration potential at steady-state. This steady-state also takes longer to occur in samples with a lower decomposition rate. Modeling data has determined that if the decomposition rate of wood could be decreased to approximately 0.1% per year, steady-state will not be reached within 1000 years.

The synthesis of these various points shows that the wood burial carbon sequestration method deserves further research. Wood decomposition can be slowed by interring the wood underground. If the decomposition rate of wood can be cut from the natural 16% per year to a theoretical value of around .1% per year, this method can sequester ever-increasing amounts of carbon for at least 1000 years. It may be possible to decrease the decomposition rates to this level by optimizing the environment in which the wood is interred. If wood can be stored below the water table, at low temperatures, and in nutrient-poor soils, the decomposition rate could be lowered enough to effectively store carbon for hundreds of years. Further research into the efficacy of this method over a long timescale is required, and appears to be warranted based on this short term study.

7.2 Directions for Future Research

The most important aspect to change for future research is time. Decomposition is a long process, and cannot accurately be simulated in 20 months.

We recommend a longer time course to firmly establish the difference in decay between woody biomass above- and below-ground. We also recommend analysis of wood already interred underground, with radiometric or other forms of dating to determine the age of the biomass. Contingent upon the results of this work, there may be need for a longer term study to examine decay over an even longer time scale.

Additionally, shorter studies focused on optimizing decomposition rates should also be conducted. These studies could alter oxygen concentration and chemical nutrients like nitrogen, while placing the wood in different temperatures and water table heights. More expansive preliminary laboratory treatments are recommended followed by field experiments with durations of 1-2 years to examine the effects of the various conditions on actual wood decomposition.

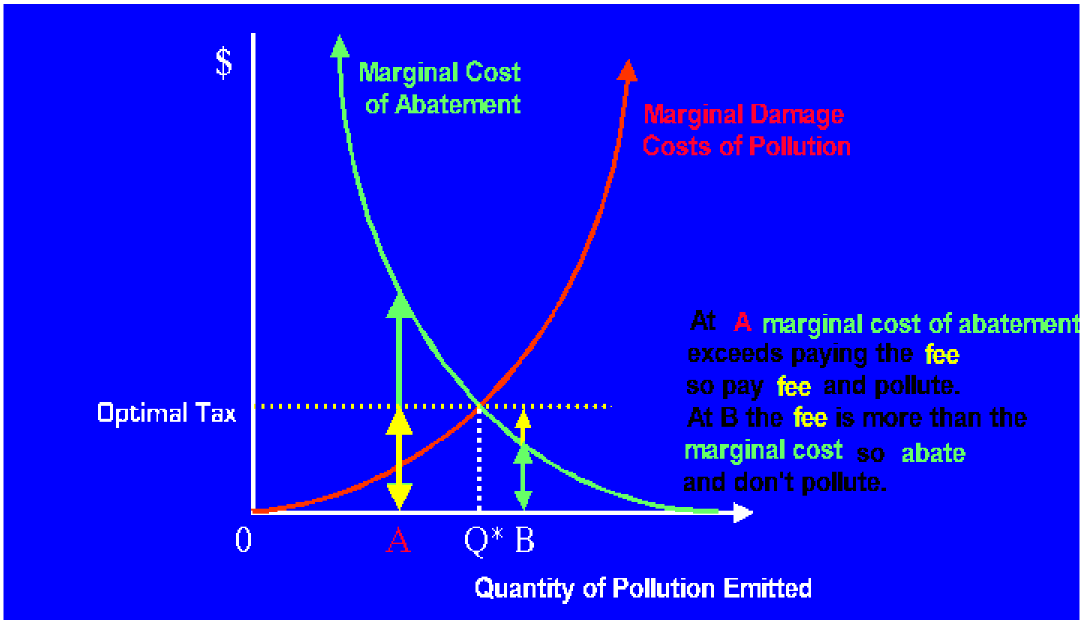
Two other important considerations that this study did not fully address are economic feasibility and ecological safety. A full analysis of the cost of the method, along with an estimate of its worth to a carbon market, must be conducted to ensure that the method could be successfully carried out and funded. It is also important to ensure that any sequestration methods avoid endangering the local ecology. Chief among ecological concerns are the impact of removing woody biomass from a forest ecosystem and the evolution of methane from anaerobic decomposition of wood. As forest management techniques have shown, it is possible to preserve or enhance the ecological productivity of a forest while removing woody biomass. Wood burial sequestration can be coupled to existing techniques of forest management to ensure forest ecosystems are not harmed by woody biomass removal. The precise guidelines which must be followed to avoid harm to the environment lay outside the scope of this experiment, but are worthy of further research. Methane emissions are also a concern, as methane is a potent greenhouse gas. We did not attempt to quantify amounts of methane emissions in our field studies. Should significant amounts of methane be released during the decomposition of interred wood, further research into the applicability and costs of methane wells will be required.

This study serves as a pilot experiment, and does not address many of the details of implementation, cost, or risk which must be determined before the woody biomass sequestration method is ready for wide-scale use. Instead, this study shows that further research with a more expansive focus is warranted.

Nevertheless, our project suggests that carbon sequestration through wood burial has the potential to be a viable option in the global effort to mitigate climate change. Our project has suggested that certain conditions which exist naturally can be enhanced to maximize the environment’s carbon sequestration potential. Taken together, the multiple facets of this research project open the door for future research and discussion about carbon sequestration via wood burial.

Appendices

Appendix I: Carbon Tax



At A marginal cost of abatement exceeds paying the fee so pay fee and pollute. At B the fee is more than the marginal cost so abate and don't pollute.

Graph developed by Professor Elizabeth Bogan at the Princeton Department of Economics

Appendix II: Soda Lime Reaction Pathway

Overall Reaction:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O + \text{heat}$$

Steps:

1) $CO_2 + H_2O \rightarrow CO_2\ (aq)$

   CO_2 dissolves in water - slow and rate determining

2) $CO_2\ (aq) + NaOH \rightarrow NaHCO_3$

   Bicarbonate formation at high pH

3) $NaHCO_3 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O + NaOH$

   NaOH recycled to Step 2 – acts as a catalyst

   Each mole of CO_2 (44g) reacted produces one mole of water (18g)

Appendix III: Soil Analysis Results

	Organic Matter			Phosphorus: Mehlich 3			Potassium			Magnesium			Calcium			pH		Acidity	CEC	% Bass Saturation			
Date	%	Rate	ENR lbs/A	ppm	rate	MD	ppm	Rate	MD	ppm	Rate	MD	ppm	Rate	MD	Soil pH	Buffer index	H, meq/100g	meq/100g	K %	Mg %	Ca %	H %
8/10/2008	2.5	L	91	61	H	69	66	L	41	84	M	67	462	L	32	4.8	6.65	2.8	6	2.8	11.7	38.5	46.2
	1.3	L	70	43	M	49	29	VL	17	55	M	45	342	L	16	4.9	6.75	1.8	4	1.9	11.5	42.8	43.9
	0.3	VL	44	6	VL	9	31	VL	18	110	M	86	590	L	48	4.6	6.46	4.7	8.7	0.9	10.5	33.9	54.1
	2.5	L	91	61	H	69	66	L	41	84	M	67	462	L	32	4.8	6.65	2.8	6	2.8	11.7	38.5	46.2
	1.3	L	70	43	M	49	29	VL	17	55	M	45	342	L	16	4.9	6.75	1.8	4	1.9	11.5	42.8	43.9
	0.3	VL	44	6	VL	9	31	VL	18	110	M	86	590	L	48	4.6	6.46	4.7	8.7	0.9	10.5	33.9	54.1
	2.5	L	91	61	H	69	66	L	41	84	M	67	462	L	32	4.8	6.65	2.8	6	2.8	11.7	38.5	46.2
	1.3	L	70	43	M	49	29	VL	17	55	M	45	342	L	16	4.9	6.75	1.8	4	1.9	11.5	42.8	43.9
	0.3	VL	44	6	VL	9	31	VL	18	110	M	86	590	L	48	4.6	6.46	4.7	8.7	0.9	10.5	33.9	54.1
	2.5	L	91	61	H	69	66	L	41	84	M	67	462	L	32	4.8	6.65	2.8	6	2.8	11.7	38.5	46.2
	1.3	L	70	43	M	49	29	VL	17	55	M	45	342	L	16	4.9	6.75	1.8	4	1.9	11.5	42.8	43.9
	0.3	VL	44	6	VL	9	31	VL	18	110	M	86	590	L	48	4.6	6.46	4.7	8.7	0.9	10.5	33.9	54.1
	2.5	L	91	61	H	69	66	L	41	84	M	67	462	L	32	4.8	6.65	2.8	6	2.8	11.7	38.5	46.2
	1.3	L	70	43	M	49	29	VL	17	55	M	45	342	L	16	4.9	6.75	1.8	4	1.9	11.5	42.8	43.9
	0.3	VL	44	6	VL	9	31	VL	18	110	M	86	590	L	48	4.6	6.46	4.7	8.7	0.9	10.5	33.9	54.1
12/8/2008	1.8	L	80	56	H	63	15	VL	8	53	M	43	392	M	23	5.1	6.78	1.5	3.9	1	11.3	50.3	37.7
	0.5	VL	50	38	M	44	34	VL	20	136	H	106	524	L	39	4.9	6.63	3	6.8	1.3	16.7	38.5	44.2
	0.1	VL	44	46	M	52	42	VL	25	136	H	106	333	VL	15	4.7	6.64	2.9	5.8	1.9	19.5	28.7	50.1
	1.8	L	80	56	H	63	15	VL	8	53	M	43	392	M	23	5.1	6.78	1.5	3.9	1	11.3	50.3	37.7
	0.5	VL	50	38	M	44	34	VL	20	136	H	106	524	L	39	4.9	6.63	3	6.8	1.3	16.7	38.5	44.2
	0.1	VL	44	46	M	52	42	VL	25	136	H	106	333	VL	15	4.7	6.64	2.9	5.8	1.9	19.5	28.7	50.1
	1.8	L	80	56	H	63	15	VL	8	53	M	43	392	M	23	5.1	6.78	1.5	3.9	1	11.3	50.3	37.7
	0.5	VL	50	38	M	44	34	VL	20	136	H	106	524	L	39	4.9	6.63	3	6.8	1.3	16.7	38.5	44.2
	0.1	VL	44	46	M	52	42	VL	25	136	H	106	333	VL	15	4.7	6.64	2.9	5.8	1.9	19.5	28.7	50.1
	1.8	L	80	56	H	63	15	VL	8	53	M	43	392	M	23	5.1	6.78	1.5	3.9	1	11.3	50.3	37.7
	0.5	VL	50	38	M	44	34	VL	20	136	H	106	524	L	39	4.9	6.63	3	6.8	1.3	16.7	38.5	44.2
	0.1	VL	44	46	M	52	42	VL	25	136	H	106	333	VL	15	4.7	6.64	2.9	5.8	1.9	19.5	28.7	50.1
	1.8	L	80	56	H	63	15	VL	8	53	M	43	392	M	23	5.1	6.78	1.5	3.9	1	11.3	50.3	37.7
	0.5	VL	50	38	M	44	34	VL	20	136	H	106	524	L	39	4.9	6.63	3	6.8	1.3	16.7	38.5	44.2
	0.1	VL	44	46	M	52	42	VL	25	136	H	106	333	VL	15	4.7	6.64	2.9	5.8	1.9	19.5	28.7	50.1
8/17/2009	1.4	L	73	50	M	57	20	VL	11	49	M	40	368	M	20	5.2	6.81	1.2	3.5	1.5	11.7	52.6	34
	0.4	VL	51	36	M	42	35	VL	21	92	H	73	456	L	31	5.2	6.77	1.6	4.8	1.9	16	47.5	33.8
	0.6	VL	53	40	M	46	52	VL	32	111	H	87	511	L	38	5	6.68	2.5	6.1	2.2	15.2	41.9	41
	1.4	L	73	50	M	57	20	VL	11	49	M	40	368	M	20	5.2	6.81	1.2	3.5	1.5	11.7	52.6	34
	0.4	VL	51	36	M	42	35	VL	21	92	H	73	456	L	31	5.2	6.77	1.6	4.8	1.9	16	47.5	33.8
	0.6	VL	53	40	M	46	52	VL	32	111	H	87	511	L	38	5	6.68	2.5	6.1	2.2	15.2	41.9	41
	1.4	L	73	50	M	57	20	VL	11	49	M	40	368	M	20	5.2	6.81	1.2	3.5	1.5	11.7	52.6	34
	0.4	VL	51	36	M	42	35	VL	21	92	H	73	456	L	31	5.2	6.77	1.6	4.8	1.9	16	47.5	33.8
	0.6	VL	53	40	M	46	52	VL	32	111	H	87	511	L	38	5	6.68	2.5	6.1	2.2	15.2	41.9	41
	1.4	L	73	50	M	57	20	VL	11	49	M	40	368	M	20	5.2	6.81	1.2	3.5	1.5	11.7	52.6	34
	0.4	VL	51	36	M	42	35	VL	21	92	H	73	456	L	31	5.2	6.77	1.6	4.8	1.9	16	47.5	33.8
	0.6	VL	53	40	M	46	52	VL	32	111	H	87	511	L	38	5	6.68	2.5	6.1	2.2	15.2	41.9	41
	1.4	L	73	50	M	57	20	VL	11	49	M	40	368	M	20	5.2	6.81	1.2	3.5	1.5	11.7	52.6	34
	0.4	VL	51	36	M	42	35	VL	21	92	H	73	456	L	31	5.2	6.77	1.6	4.8	1.9	16	47.5	33.8
	0.6	VL	53	40	M	46	52	VL	32	111	H	87	511	L	38	5	6.68	2.5	6.1	2.2	15.2	41.9	41

	Organic Matter			Phosphorus:			Potassium			Magnesium			Calcium			pH		Acidity	CEC	% Bass Saturation			
Date	%	Rate	ENR lbs/A	ppm	rate	MD	ppm	Rate	MD	ppm	Rate	MD	ppm	Rate	MD	Soil pH	Buffer index	H, meq/100g	meq/100g	K %	Mg %	Ca %	H %
12/7/2009																							
	2.3	L	90	59	H	67	155	VH	99	75	M	60	305	L	12	4.9	6.73	2	4.5	8.8	13.9	33.9	44.3
	0.5	VL	51	13	VL	17	66	L	41	114	H	89	530	L	40	5.1	6.7	2.3	6	2.8	15.8	44.2	37.8
	0.6	VL	54	18	L	22	63	L	39	104	H	82	508	L	37	5.2	6.75	1.8	5.4	3	16	47	34.2
	2.3	L	90	59	H	67	155	VH	99	75	M	60	305	L	12	4.9	6.73	2	4.5	8.8	13.9	33.9	44.3
	0.5	VL	51	13	VL	17	66	L	41	114	H	89	530	L	40	5.1	6.7	2.3	6	2.8	15.8	44.2	37.8
	0.6	VL	54	18	L	22	63	L	39	104	H	82	508	L	37	5.2	6.75	1.8	5.4	3	16	47	34.2
	2.3	L	90	59	H	67	155	VH	99	75	M	60	305	L	12	4.9	6.73	2	4.5	8.8	13.9	33.9	44.3
	0.5	VL	51	13	VL	17	66	L	41	114	H	89	530	L	40	5.1	6.7	2.3	6	2.8	15.8	44.2	37.8
	0.6	VL	54	18	L	22	63	L	39	104	H	82	508	L	37	5.2	6.75	1.8	5.4	3	16	47	34.2
	2.3	L	90	59	H	67	155	VH	99	75	M	60	305	L	12	4.9	6.73	2	4.5	8.8	13.9	33.9	44.3
	0.5	VL	51	13	VL	17	66	L	41	114	H	89	530	L	40	5.1	6.7	2.3	6	2.8	15.8	44.2	37.8
	0.6	VL	54	18	L	22	63	L	39	104	H	82	508	L	37	5.2	6.75	1.8	5.4	3	16	47	34.2
	2.3	L	90	59	H	67	155	VH	99	75	M	60	305	L	12	4.9	6.73	2	4.5	8.8	13.9	33.9	44.3
	0.5	VL	51	13	VL	17	66	L	41	114	H	89	530	L	40	5.1	6.7	2.3	6	2.8	15.8	44.2	37.8
	0.6	VL	54	18	L	22	63	L	39	104	H	82	508	L	37	5.2	6.75	1.8	5.4	3	16	47	34.2

Values on this report represent the plant-available nutrients in the soil.

Rating after each value:

VL (Very Low)
L (Low)
M (Medium)
H (High)
VH (Very High)
ENR (Estimated Nitrogen Release)
CEC (Cation Exchange Capacity)

Explanation of symbols:

% (percents)
ppm (parts per millions)
lbs/A (pounds per acre)
ms/cm (mili-mhos per centimeter)
meq/100g (milli-equivalent per 100 grams)

Conversions:

ppm x 2 = lb/A
Soluble Salts ms/cm x 640 = ppm

Appendix IV: Technical Description of JABOWA-CS

1. Changes to the Code

To provide the user with as complete of a set of documentation as possible in understanding JABOWA-CS, we have written a technical description. This documentation is missing from the originally purchased JABOWA package. Note that while our description technically refers to our own implementation of JABOWA-CS, the vast majority of the documentation is also applicable to the original JABOWA source code.

We list in this appendix every .cpp file inside the JABOWA source and describe the functionality of each file, if understanding is relevant to JABOWA-CS. Team Carbon Sinks does not attempt to provide a technical description of all aspects of the JABOWA model, but rather only the parts relevant to the creation of our modification of it.

Italic function names indicate files that are irrelevant to the core model functionality - they are composed largely of helper functions to the JABOWA application. This means alterations to these files might affect the functionality of the *software*, but not the *model*. **Bold function names** indicate files that were changed to implement Carbon Sinks code and functionality in the JABOWA code. Files may fit in both categories (relevant to model functionality and altered by Carbon Sinks) or neither categories (composed of support and helper functions, and not touched by Carbon Sinks). In addition, any lines of code edited by Carbon Sinks are set off in the code itself by comments indicating they have been altered.

Implicit in this documentation is that the JABOWA III code and literature was used and altered to make JABOWA-CS (Botkin, 1993).

1.1. Birth.cpp

As is evident from the title, this file contains the code where trees are born and generated.

1.2. Climate.cpp

This file performs model-related calculations on the temperature and precipitation data provided to the model. This data is read from a weather file (such as "loblollyWthrNor.txt") from JABOWASOURCE/Data.

1.3. *CommunitiesParamDlg.cpp*

1.4. *Cursor.cpp*

1.5. *db.cpp*

1.6. **Death.cpp**

Contains the code that determines when trees die a *natural* death (due to logging or overcrowding). This distinction is important, as artificial deaths accomplished through disturbances are executed in Disturb.cpp.

This file contains the most unique Carbon Sinks edits that change core functionality. When trees die, their data is no longer thrown away from the model. It is instead stored in a data structure that closely mirrors the data structure used to keep track of living trees. A special virtual tag is also appended onto the tree keeping track of the method by which it died.

In addition, decay code is stored here - this is where the DECAY() method is stored. This method calculates the amount by which a given log has decayed.

1.7. **Disturb.cpp**

Contains the code that determines when a tree dies an *unnatural* death (by logging or wind throw). Again, Carbon sinks code was added to ensure trees would be moved to the proper data structure once dead. A tag is added to note that the tree died due to either logging or wind throw. Currently, the Carbon Sinks-edited JABOWA model does not make use of the wind throw functionality; all trees dying through Disturb.cpp's code is assumed to have been logged and removed by humans.

1.8. *Draw.cpp*

1.9. *Errlog.cpp*

1.10. *Fonts.cpp*

1.11. ***Globals.cpp***

Data Structure definitions are stored here: JABOWA-CS has a new data structure that allows the storage of dead trees.

1.12. *Graphics.cpp*

1.13. *GraphicsOutputParamsDlg.cpp*

1.14. GraphicsWindow.cpp

JABOWA is run and executed from a graphical user interface (GUI). This interface is in charge of calling the controls code. Every time a year is iterated, the following methods are called:

- BIRTH()
- GROWTH()
- DEATH()
- DECAY()

- RESULTS()

These functions exist in the appropriately named files.

1.15. Growth.cpp

The main function in Growth.cpp is GROWTH() - it iterates through every tree in the current plot of forest and calculates how much the tree should grow in size and mass.

1.16. *InputOutputParamsDlg.cpp*

1.17. *JABOWA3.cpp*

Actually does very little outside of initializing the GUI.

1.18. *JABOWA3Dlg.cpp*

1.19. *JABOWAWindow.cpp*

1.20. *Loadinit.cpp*

Loads the initialization file (e.g. "loblollyInitNormalParams.txt") from the JABOWASOURCE/Data folder.

1.21. *Loadplot.cpp*

Loads plot data from the plot data file (e.g. "loblollyPlot.txt") from the JABOWASOURCE/Data folder.

1.22. *Loadspp.cpp*

Loads all species data from the text file allSpecies.txt in the JABOWASOURCE/Data folder.

1.23. *LoggintParamsDlg.cpp*

1.24. *MainWnd.cpp*

1.25. ***Menus.cpp***

A minor change was implemented - unfortunately many data structures are statically hard coded in JABOWA, for example the number of "communities." In this particular file, a function had to be modified to accept the new "Eastern Shore" community I had created.

1.26. *MFCHelpers.cpp*

1.27. *rand.cpp*

The pseudorandom algorithm is deterministic. Although it should provide an evenly distributed set of random numbers, it will grow the same forest every time unless the random number seed (provided in your "init.txt" file) is changed.

1.28. *Registration.cpp*

This file, as well as RegistrationDlg.cpp, handle licensing and registration of the GUI executable.

1.29. *RegistrationDlg.cpp*

1.30. ***Results.cpp***

Prints the results of the simulation, the major parameters within the model, to a .txt file. There is a complete output file and a more simplified one - the simplified output was created as we are concerned solely with biomass at the moment.

1.31. *ScrollStopDialog.cpp*

1.32. *secdib.cpp*

1.33. *seciimage.cpp*

1.34. Site.cpp

Interprets the climate and weather data and processes it into parameters that the model can use and understand.

1.35. *SiteInfoParamsDlg.cpp*

1.36. *Sort.cpp*

1.37. *SpeciesParamsDlg.cpp*

1.38. startup.cpp

Initializes the forest simulation - loads parameters from text files into the appropriate data structures.

1.39. *StatResultsDlg.cpp*

1.40. *Stats.cpp*

1.41. *StdAfx.cpp*

1.42. *Treeplot.cpp*

1.43. *Vid_init.cpp*

2. Changes to Associated Data Files

As mentioned above, new data files must be provided to JABOWA to create a new simulated forest with a different environment and tree species. JABOWA, unfortunately, is not coded to be modular. Many data structures are static (they must be altered to expand to allow more species or climate inputs) and the code tends to be coded to expect a hard coded number of possibilities (functions need to be altered to accept new communities).

JABOWA-CS attempted to alter functions and data structures where appropriate to accommodate a new forest. This involves:

- A new species

Loblolly Pine was not currently a part of JABOWA's database of tree species, so we looked up new tree species model parameters to incorporate it into JABOWA-CS.

These parameters were all pulled either from literature or determined empirically relative to a related species, White Pine. Team Carbon Sinks could not successfully get around the hard-coded maximum of 40 species stored in JABOWA, and so deleted White Pine from the database to make room for loblolly pine.

- A new "community" (also interchangeably called "habitats")

A "community" is an association of tree species - the species composition of a forest. One of the assumptions we make so our results are easier to interpret is that our community is composed solely of loblolly pine. We were only incompletely able to implement a new community into JABOWA. While we are in fact using a newly created community dubbed "Maryland Eastern Shore," we were not able to alter the autogenerated GUI code to accommodate a larger number of available communities. Community selection happens from the GUI. Thus, when the GUI is started, "Maryland Eastern Shore" is automatically loaded as the default, even though the Community selection field reads blank. As long as the user makes no new selection for community, a forest using the "Maryland Easter Shore" habitat will be simulated.

- A new weather file

The weather file stores sample weather data that will be used to calculate a climate parameter. JABOWA needs month-by-month temperature averages (in Fahrenheit) and rainfall (in inches). Our weather data was obtained from the National Climate Data Center and gathered by a weather station near Queenestown, MD where Wye Labs was situated. Approximately 60 years of temperature and precipitation data was used.

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