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Current industrial agricultural practices are rapidly depleting soil nutrients, making much arable land unusable. With today's exponential population growth, it is more important than ever that croplands are reconstructed to allow for sustainable food and fuel crop growth. Fuel, in particular, is a major concern, due to the eminent increase in energy usage that has contributed to a continuing rise in atmospheric greenhouse gas concentration. Closely observing agricultural practices of indigenous cultures that use intercropping provides a model for sustainable crop growth; this model can be developed and tested over an extended period of time. Once a successful practice is established, the biomass that is produced efficiently can then be converted into ethanol as an alternative fuel source. Although development of successful intercropping agriculture can take up to fifty years to complete, an intermediary step that can be taken in the meantime is low-diversity, high-density intercropping. In particular, pairing grasses with a nitrogen-fixing legume is optimal. The following studies show examples from agricultural research; however, the intermediary step proposed is optimal for use in cellulosic biofuels.

The implications for agricultural practices include the fact that "sophisticated management must be based upon recognition of likeness between ecological units" (Posey 1985). The likeness referenced is the interaction between biological units which forms an interconnected system of ecology. With this understanding, sustainable agricultural practices can be developed. The current industrial practices of agriculture prove to be unsustainable due to soil diversity loss, use of petroleum products, and need for pesticides, stemming from a lack of emphasis on beneficial ecosystem interactions. Therefore, farmers and agronomists alike might better seek other more ecologically fitting crop systems. Across the world, indigenous peoples have been using sustainable agricultural practices since the domestication of plants. For example, biodiversity is increased in the largest forest on the planet, the Amazon, by the Kayapo Indians. They manage and conserve forest patches based on temperature, moisture, and shade level requirements of desired plants and have processes for utilizing the secondary forest growth. For them, knowledge of the plants and the environment in which they grow is crucial. With this knowledge, the Kayapo use ecological zones within the forest to create areas known as *apete,* including*apete-nu* (newly formed vegetative clumps), *apete ngri*(forest plot with some trees and large shrubs), and*apete (kumrenx*) ("real *apete*"with shade from tall trees). They begin by making their own mulch that includes living ants and termites, which not only make the mulch nutrient- rich, but also fight off unwanted predators such as leaf-cutting ants. Every part of the *apete* has a use, whether for food, medicine, materials, fuel, shade, or protection. Annual controlled burns rid them of pests and weeds. By intercropping, the fields can be utilized for up to forty years; beyond those forty years, the secondary forest has use, too. In order to modify effects of secondary forest growth, they utilize a sort of companion planting, where species mutually benefit from one another's growth.For example, banana trees provide a microclimate for tubers and medicinal plants.

The Native Americans also traditionally utilized intercropping. The southwestern tribes planted a mosaic of corn varieties which created an over story for plants such as grain amaranths, squashes, beans, chilies, tomatoes, and greens. When planting, they spaced each plant apart from the next, creating room for each individual plant to flourish (Nabhan 1992).Both of these historical examples of intercropping show past successes that can function as a model for implementation in modern systems of agriculture. In particular, the use of mulch to ward off pests and weeds and the use of specific species combinations to boost biodiversity and biomass yields offer significant benefits for long-term crop production. The following agricultural studies support this beneficial claim.

Agricultural systems of the industrial world are currently dominated by monoculture fields. Single species growth allows for the rapid and efficient harvest of crops. Additionally, a farmer can spray herbicide and pesticide on the crops that will kill any living organism other than the crop itself. The consequences of using these chemicals on single crop systems are, however, drastically affecting the local fields by creating biodiversity loss, nutrient-dead zones, water waste, and soil loss. Monocultures "lack the inherent protection against fungi, bacteria, viruses, anthropods, and weeds" and therefore require pesticides and fertilizers (Cox and Jackson 2002). Due to this loss, fields are rapidly depleted of usefulness, and, in turn, more land must be converted into agricultural space. Arable land, however, is not infinitely available on earth. Monocultures also affect the environment on a large scale due to the excess amounts of fertilizer and pesticides running off into nearby ground and surface water, reducing the water's quality (Glover 2003). These contaminated waters then flow into the oceans, creating hypoxic zones where no life can thrive. For example, a shocking 20,000 square kilometers of ocean in the Gulf of Mexico is currently a dead zone, which is a three hundred percent increase in nitrogen load in the past fifty years (Glover 2003). Scientists are currently studying more effective agricultural practices, including perennializing food crops; high-density, low-input fields; and bicultures. Additionally, important solutions for pest control and increasing biomass yields are being researched, from soil contents to species pairing.

The Land Institute is currently working to perennialize food crops. This innovative idea for new crops provides an avenue for future intercropping of grassy species that can serve as both food and fuel. This reversion can serve to prevent soil nutrient loss, conserve resources like petroleum and water, manage pests and weeds, and create high yields of both food and fuel crops. In order to mimic the native vegetation that once covered the majority of the land that is now America's crop land, researchers at the Land Institute are both perennializing annual crops (such as wheat, sorghum, and sunflower) and domesticating wild perennials like Illinois bundleflower, wheatgrass, and compass plant. They chose these particular plants since they are good candidates for perennializing by breeding for many traits rather than genetically modifying them for a single gene. The Land Institute predicts that the process of perennializing species will take anywhere from twenty-five to fifty years to complete (Glover 2003). In the meantime, there are intermediary steps that can be taken.

In a ten-year study done by David Tilman and a team of researchers on low-input, high-diversity grasslands, the findings suggest that a switch from monocultures could be beneficial in biomass yields. The research was carried out on nitrogen-poor sandy soils, which were previously devastated by agricultural use. This is a significant model of how previously misused lands can be made biologically diverse and viable once more. The team planted combinations of one, two, four, eight, or sixteen species of perennial herbaceous grasses on 168 plots. Each year, biomass yield measurements were taken for each plot, and both soil and root CO_2 sequestration was calculated.Over the span of ten years, the amount of biomass produced and carbon dioxide sequestered increased. With the increase in species numbers on each plot, the biomass and CO_2 sequestered increased, too. Higher biomass yields mean more crops to convert into energy or food. Another positive aspect of higher diversity is a decrease in greenhouse gases, CO_2 in particular, through root and soil sequestration.

Additionally, the fruitful results from poor soils mean that new land does not need to be cleared for energy crops and that energy crops will not compete for land with food crops. Perennialized food crops could even be integrated. The study found that the plots of single species required fertilizers and pesticides to have high yields, while highly diverse plots did not. This result is, in part, due to the presence of nitrogen-fixing legumes in higher diversity treatments. Also, these diverse plots were seventy percent more stable than their monoculture counterparts (Tilman *et al.* 2006). It is important to note the experiment time period and that it was done on a very specific soil type and climate area. This means that many experiments will be required to find the right combination of plants for every soil type across the United States, and this will take time. Through data analysis, Tilman *et al*. (2009) have also shown that biculture plots do well when a grass was paired with a legume. This pairing proves to be an effective intermediary step for biofuel grass fields while research continues on soil and climate stipulations for ideal intercropping systems.

When thinking about intercropping species, it is important to consider the optimal combination rather than the highest amount of diversity. This notion is backed by results from the Tilman experiment: "[I]n the first two years, biomass was greater in the 2-species plots than 16-species plots… [and] was similar in later years" (Tilman 2009). These plots had "near-maximum biomass yields" and sequestered more carbon (Tilman 2009). For efficient harvesting, the legumes could be planted in clumps evenly spaced throughout the field. This biculture system could eventually be effective with the perennialized crops being created by the Land Institute or other research groups.

A similar study by Andy Hector and Robert Bagchi (2007) on "biodiversity and ecosystem multifunctionality," presented the same conclusion as Tilman's (2006): that biodiversity has a positive effect on ecosystem productivity and stability. In this experiment, both above- and below-ground net biomass production and nitrogen levels, along with light availability and decomposition of lignin and cellulose in multiple grassland ecosystem sites, ecosystem functions, and species were considered. After identifying the specific ecosystem processes that each species affected, they planted species in subsets according to the specific ecosystem process desirable to each site. Results expressed a mean number of species per process as 3.2-6.6. The number of species affecting above ground biomass ranges from 4-8 and the spectrum of unconsumed soil nitrogen is 2-7. This means that different processes, such as yield and sustainability, are affected by multiple species, and therefore biodiversity is important in maintaining a multifunctional ecosystem. A multifunctional ecosystem, one with multiple species filling various niches, would provide everything crops need to flourish: light (resulting from varied species height and density), nutrients (nitrogen and other products of decomposition), and sufficient water flow (with increase in robustness of soils).

The issue of biodiversity encompasses not only crop yields but also weeding requirements. Expanding on the above research, Hector *et al*. (2007) published the paper entitled "Biodiversity and ecosystem functioning: reconciling the results of experimental and observational studies," which discusses the controversies around the BIODEPTH experiment by Thompson *et al.* (2005), and similar experiments and surveys on biodiversity.This paper focuses on the issue of legumes; it agrees with Tilman that nitrogen-fixing legumes positively affect biomass yields and claims they have an effect on species' richness. Weeding had a huge effect on biodiversity experiments and observational studies. Once weeding was ceased, low-density fields gained biodiversity and high-density fields lost biodiversity due to the invaders. It is important to note that the Tilman experiment did have weeding in place, which is highly artificial. This leads to another conclusion, which is that competition and environmental conditions play a large role in biodiversity results. In order to find optimal species combinations, which could prevent the need to weed, it is important to conduct time-consuming studies at every site that is chosen for high-density intercropping. This research therefore demonstrates that a low-diversity, high-density intercropping system could be used productively in the meantime.

In order to solve the issue of weeding by increasing biodiversity, a study on competition of neighboring plants was conducted in 2009 by T. Wyszomirski and J. Weiner. Ecosystem conditions affect plant size, and there is a positive correlation with neighboring plant size. This can be attributed to local density dependence (also available nutrients), mortality patterns, genetic relatedness, or facilitation.In contrast, there is a negative correlation between neighboring plant size due to the death of smaller, outcompeted plants and spatially uniform crop rows, in the manner that most monocultures are arranged. This is another explanation for the lower biomass yields of monoculture fields. Spatial uniformity, like the Native Americans utilized, is also a solution for weed control, which will be explored later.

The importance of finding ideal crop combinations relates to issues of nitrogen leaching, soil carbon accumulation, and invasion by pathogens and pests, as well as weed prevention. Weiner *et al.* (2010) also researches species combinations to eliminate weedy species. He suggests that group selection rather than individual selection is necessary for achieving this in fields, even though it is not commonly seen in nature. Agriculturalists must know not to reduce or remove genetic variation in a population, as this can lead to individual selection. Selecting genotypes that better the community under any agricultural conditions will vastly affect yield, which is a variable of the population and not the individual. Good candidates for selection include those plants bred to have increased sustainability or yield and are therefore not advantageous to the individual plant. In the article, the authors also argue that higher density will not only increase competition but also allow the opportunity for cooperation between plant species as they grow at different rates and to differing heights. This mutual aid can lead to a decrease in the amount of weeds in a crop field. Weeds, when present, vastly reduce yields (Weiner *et al.* 2010). This is similar to the strategy of the Kayapo Indians who use species pairing in their native agricultural practices. The plants they choose to plant near one another provide necessary variables for one another; for example, the banana trees provide shade for tubers and other shade plants (Posey 1985).

Specifically regarding weed suppression, the study by Weiner *et al. (*2010*)* suggests four guidelines to finding success in crop choices. These are 1) good competitive ability; 2) initial size advantage over weed species; 3) advantage of large initial size that increases with density; and 4) total biomass production that does not decrease at high densities. Increased spatial uniformity may also play a crucial role in weed suppression among high-density crop fields. High density may increase the spread of some disease; therefore, uniformity would prevent the spread of others. This can be attributed to an increase in the availability of resources allotted to each individual plant, since space where these needed vectors are found is increased via uniform planting. Additionally, the initial allotted space will allow for the plants to outcompete the smaller weed seedlings before growing into mature plants, at which time they will begin to compete with one another. They suggest that cereal crops are the most successful. It is interesting to note that the crops The Land Institute is working to perennialize are cereal crops. The elimination of the need for herbicides could possibly outweigh the need for new harvesting methods of high-density fields. It will also decrease the labor (both human and machine-performed) needed to suppress weedy species, since the diverse species planted would do the work (Weiner *et al.* 2010).

Weiner also notes that sustainability is a desired variable in the group of species selected. The article discusses high biomass's leading to an increase in sustainability. It follows that higher biomass means higher amounts of decomposing plant materials, which contribute to soil fertility. This is true of natural habitats but not those created by the agriculture of today, when the excess biomass is cleaned from fields after harvest (Weiner *et al.* 2010). Just as the Kayapo Indians would make their own mulch containing ants and termites, it is very important to have knowledge of soil composition and its effects on sustainability and biomass production (Posey 1985).

Another ecologist, M. Scherer-Lorenzen, agrees that decomposition plays a significant role in ecosystem functioning and adds that decay is influenced by diversity. These ecosystem functions resulting from below-ground biodiversity include yield and sustainability, which are necessary for successful development of biofuel crops. He begins by stating that different species breakdown at different rates and that decomposer (fungi, bacteria, and soil fauna) activity is affected by differing species and habitat conditions.He predicted that functional variability rather than taxonomic variability will create the biggest control on successful, high-yielding ecological processes. He performed a two-year experiment measuring the decompositional rates of standard materials and plant litter with increasing functional diversity. The results proved that legumes significantly increased decomposition rates and showed that furthering biodiversity in general affects decomposition. The decomposition in turn adds to the success and abundance of productivity. Nitrogen in the soil, presumably from legumes, increases decomposition rates and encourages decomposers like earthworms to enter the area (Scherer-Lorenzen 2008).

The findings of Scherer-Lorenzen (2008) support the earlier findings of Tilman *et al*. (2006), showing that legumes grown in combination with grasses in bicultural fields affect both yields and decomposition rates. It therefore follows that this combination also increases the amount of litter available to be decomposed. Since the processes of nutrient flow that further sustainability are cyclical, the amount of detritus leads to either a deficiency or an adequate amount of nutrients in the soil that can reenter the cycle through new plant growth. Adequate nutrient availability leads to rapid growth and also rapid decomposition, making turnaround times for harvest more rapid and abundant (Scherer-Lorenzen 2008).These feedback loops will need to be studied for each specific site in order to create an ideal ecosystem of combined species. This is another time-consuming effort which can be mediated by high-density bicultures of legumes and a grass species.

In addition to soil composition from decomposition, the presence of arbuscular mycorrhizal fungi (AMF) increases above-ground biomass of grasses. AMF is another below-ground vector for sustainable yields; it is a fungus that grows in the roots of certain plant species. When competition between plants begins to occur, AMF can allow for nutrient uptake to be more efficient, possibly allowing for greater survival of a greater number of plant individuals. This is true if competition for space occurs at the roots where nutrient uptake occurs or if nutrients are not highly available in the soil. In a study done by Zhang *et al.*(2010),high AMF concentrations led to a higher above-ground competition, which resulted in an increase in biomass production and decrease in density of individual plants. They also found that low AMF concentrations were very effective in increasing root biomass and would also cause a decrease in density, although less so (Zhang *et al.* 2010*)*. For agricultural practices, the goal is to maximize above-ground biomass. Therefore, a high concentration of AMF should be encouraged in order to grow on chosen crop plants.

In order to determine how soil types affect the ability of AMF to increase above-ground biomass, Wagg *et al.* (2011) executed their study in two different soil types.In their research, the team discovered that effects on biomass were similar in soils with high and low sand components. This means that even under different environmental conditions, AMF can affect biomass production even though they perform different functions. These functions are determined depending on the need for a single or multiple AMF species (Wagg *et al.* 2011). This suggests that the particular soil upon which crops will be planted needs to be tested in order to identify the ideal AMF species for maximum biomass production. Additionally, there are many other species which can affect the soil composition best suited for crop growth. This may take some time to demonstrate; for example, this particular experiment only lasted twenty-five weeks. Knowledge regarding long term effects would be essential, and in the meantime, bicultures would be an ideal intermediary step, particularly bicultures that include nitrogen-fixing legumes and a grass.

Finding an effective method of agriculture is particularly pertinent to the field of energy studies. Cellulosic biofuels are an effective alternative to oil, and processing techniques are becoming cheaper and more efficient. These fuels are produced by converting plant biomass into usable energy forms. A goal when producing a sustainable energy crop is for it to "have no—or preferably positive—impacts on biodiversity," as is the goal for all agricultural systems explored in this paper (Zegada-Lizarazu *et al*.

(2013). High-density, low-impact agriculture (like that studied by Tilman), perennialized crops (like those that the Land Institute is creating), and the knowledge of plant and plant soil composition interactions all play a role in the future of biofuel crop development. The sustainable fields suggested by Tilman; long-term, high-density, high-diversity fields; and short-term bicultures would be ideal models for biofuel grass production. This is true since grasses are principally used for converting into biofuels, and Tilman's experiments deal particularly with grasslands (Zegada-Lizarazu *et al*. 2013). A long-term goal could be to integrate the perennialized crops from the Land Institute with the fuel grasses and legumes. While scientists determine ideal crop combinations and soil microbe interactions, the bicultures of fuel grasses and legumes would be the short-term goal for reaching sustainable fuel crop production.

Where monocrops fail, intercropping can succeed. Intercropping leads to increased biomass, sustainability, decreased pesticide use, decreased herbicide necessity, and more robust soils compositions where AMF and other soil species that assist nutrient uptake can flourish. Following these facts, intercropping of high-density, high-diversity, low-input fields are a common goal of agriculture for food crops and fuel crops alike. While finding ideal crop combinations for each specific soil type and ecosystem niche will take years of research, there is an intermediary step.The best solution for the short-term production of sustainable crop fields is evenly spaced, low-diversity, high-density, low-input cropping systems.

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