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A Recommendation for Polyculture Agriculture to Reduce Nitrogen Loading That Leads to Hypoxia

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A RECOMMENDATION FOR POLYCULTURE AGRICULTURE TO REDUCE
NITROGEN LOADING THAT LEADS TO HYPOXIA

by

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A Thesis Submitted in Partial Fulfillment
of the Requirements for a Degree with Honors
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ABSTRACT

The natural cycle of nitrogen is an essential part of both plant growth and crop production, but in recent years there has been an increase in nitrogen through the use of synthetic fertilizers. Agricultural surface runoff can carry away the converted, mobile nitrate nitrogen into downstream systems leading to an unnatural influx of nitrogen. This increased nutrient load can stimulate algal growth in the marine ecosystem which can cause an oxygen depletion. When the dissolved oxygen levels fall, the area is deemed 'hypoxic' and can no longer support most aquatic life. In recent decades, industrial agriculture has used monoculture practices, which are heavily governed by the use of synthetic fertilizers, to meet crop demand but employing the practices year after year strip away nutrients from the soil. In response, best management practices (BMPs) have been established to reduce the use of synthetic fertilizers and their adverse effects on the environment but a lesser used agricultural practice is polyculture, although utilizing these practices also reduces nitrogen demand. This study looked into both BMPs and polyculture in a comparative light to showcase the benefits of utilizing polyculture practices to reduce both nitrogen demand and hypoxic conditions in downstream systems. A focus was also made to provide recommendations as to when and where polyculture agriculture should be employed to maximize the benefits.

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Introduction

The earth as an ecosystem has been able to sustain itself and balance its resources long before humankind ever set foot on it and figured out how to mimic natural processes for our own purposes. As our technology has grown, so too have we begun to stray from natural processes towards modernization and maximizing productivity. In the short-term, these new ideas can be seen as technological triumphs but long-term are unsustainable; in recent decades, our solution to these unsustainable technologies has been to invest more towards modernization when a shift back to more natural and traditional ways would produce more long-term solutions.

Hypoxia

As most organisms on earth utilize oxygen (O_2) for life processes, the presence of O_2 has become an integral part of every ecosystem. Problems begin to arise should that presence of O_2 decrease below normal levels or disappear completely. The amount of O_2 that has been dissolved or absorbed into a body of water is known as its dissolved oxygen (DO) concentration; O_2 usually finds its way there through diffusion or photosynthesis, amplified by surface water mixing through wind and waves (USDC & NOAA, 2004). When this concentration drops below a certain level, usually 2-3 ppm (EPA, 2017e), it becomes “too low to support most aquatic life” and the waters are deemed hypoxic (NCCOS, 2016). Should these bottom water DO concentrations drop to around zero, the waters are deemed anoxic (Radke, 2015).

An ecosystem faced with a depleted DO concentration overtime or in several cases can become a ‘dead zone’. Unable to support aquatic life, mobile species will often leave the area in search of better conditions leaving behind immobile species, like plants that require flowing water to carry their seeds to reproduce and populate the area, that are most likely unable to survive the hypoxic conditions (NCCOS, 2016). These ecosystems normally “teeming with life become, essentially, biological deserts” where the term originated from (USDC & NOAA, 2014b), and over 166 dead zones have been documented nationwide (EPA, 2017f) which can be seen in Figure 1. Dead zones act as invisible traps for mobile species, as many cannot detect the lack of oxygen before swimming into it, and the lack of oxygen causes them to lose consciousness and die shortly after. These extreme changes in oxygen can impact fish biology such as organs becoming smaller and females unable to reproduce enough to keep the species alive; bottom-dwellers are also hit hard with the lack of oxygen stunting their growth, both scenarios affecting the biodiversity of the area along with the ecosystem food webs (VIMS, 2017). Naturally, dead zones result from stratification due to temperature or salinity leading to a lack of mixing but shallow coastal and estuarine waters have seen an increase in relation to “anthropogenic sources and an increase of nutrient inputs” (EPA, 2017e).

While the amount of O₂ in a body of water fluctuates naturally, seasonally and over longer periods of time, and over half of estuaries experience hypoxic conditions in a given year, in recent decades the most common cause is human-induced factors including nutrient loading (USDC & NOAA, 2014a). This influx of nutrients into an aquatic ecosystem promotes algal growth and increases population of algae species, which does

work to the advantage of the ecosystem in the beginning (EPA, 2017e). As these algae dies off, it sinks to the bottom to decompose. This decomposition process, carried out by bacteria, requires the intake of O₂ which “depletes the supply available to healthy marine life” (USDC & NOAA, 2014b). While this is normally a regular part of the ecosystem cycle, the algal population boom from nutrient loading leads to a higher demand of O₂ than what is present and leads to a depletion of DO. Many nutrients can contribute to the eutrophication to hypoxic zone phenomenon, where over 400 hypoxic zones have been found worldwide (EPA, 2017e), but the main elements are phosphorus and nitrogen.

Nitrogen

Hypoxic waters generally derive from eutrophication of the aquatic ecosystem where excessive nutrient inputs are introduced. Currently, it could be argued that eutrophication is the biggest source of pollution for estuaries globally (Howarth et al., 2000). Eutrophication specifically caused by excessive inputs of phosphorus and nitrogen continues to grow as an issue for estuaries, rivers, and coastal oceans. These excessive inputs, or nutrient loading, “is the most common impairment of surface waters in the US” (Carpenter et al., 1998). The Environmental Protection Agency (EPA) estimated high concentrations of nitrogen in 28% of the total stream length in the United States back in 2013 (USDC & NOAA, 2014a) with the nitrogen transport to the oceans only increasing (Carpenter et al., 1998).

Nitrogen has been linked to eutrophication most often in most temperate estuaries and coastal ecosystems (Carpenter et al., 1998). As a naturally occurring element, nitrogen is the most abundant gas in the atmosphere and essential to aquatic and

terrestrial plant growth as many metabolic processes rely on it (Randall & Mulla, 2001). While sixteen of the periodic elements are considered essential for plant growth, six macronutrients (N, P, K, S, Ca, Mg) are needed in “relatively large amounts and must often be added to the soil for optimum crop production” (EPA, 2017b). As such, nitrogen is one of three most often limiting nutrients to crop production due to its cycle; plants absorb the essential nutrients from the soil to become incorporated into phytomass, after death the phytomass is decomposed and the nutrients are returned to the soil to complete the cycle (EPA, 2017c). The nitrogen cycle sees a continuous supply through natural processes of mineralization and nitrification but anthropogenic sources contribute as well, like fertilizers (Randall & Mulla, 2001), and nitrogen is artificially added to the soil in the greatest amount of any plant nutrient (EPA, 2017c). A more detailed visual of this N cycle can be seen in Figure 2.

As world population and food demand increased, so too did fertilizer use as a high nitrogen content of the soil provided a good crop yield. Plants “cannot directly convert atmospheric nitrogen to soluble nitrogen compounds” sparking research to artificially convert inactive nitrogen gas to nitrogen compounds which the Haber-Bosch Process accomplished in the early 20th century. The Germans determined the proper conditions (high temperature and high pressure) and catalyst (iron oxides being cheapest) for creating ammonia gas but it was not until the 1930s in the United States that led to methods allowing ammonia to be directly added to the soil as a fertilizer. Today, the use of fertilizers is over 400% that of what was used in 1940 (Zmaczynski, 2017) or roughly 80×10^6 Mg/yr which equates to approximately half of the food produced in the world is supported by the use of nitrogen fertilizer. While there are a number of organic sources of

nitrogen used as fertilizer, by this point much of this nitrogen is sourced from the application of inorganic nitrogen fertilizer (Carpenter et al., 1998).

Of the fertilizers applied on cropland, only 18% of the nitrogen is removed as produce leaving behind, on average, 174 kg/ha*yr of surplus nitrogen. This surplus is the underlying cause of nonpoint source (NPS) pollution from agriculture with the ultimate cause being an excessive use of fertilizer (Carpenter et al., 1998) and correlates to dead zones around the world as shown in Figure 3. This fertilizer use being the primary source of nutrient pollution from agricultural lands (EPA, 2017i) which has become America's "most widespread, costly, and challenging environmental problem" as it is NPS (EPA, 2017h). NPS inputs derive from extensive areas of land making it hard to change practices in order to reduce the nitrogen input in this form; of the 6663×10^3 Mg/yr of nitrogen from NPS, however, almost half has been identified as originating from cropland (Carpenter et al., 1998). Agricultural NPS has been attributed to the leading source of water quality impacts (EPA, 2017g) with total nitrogen concentrations almost nine times greater downstream of agricultural lands compared to forested areas (Randall & Mulla, 2001). Similarly, NPS of nitrogen are almost nine times greater compared to nitrogen inputs from wastewater treatment plants when looking at the North Atlantic Ocean (Carpenter et al., 1998).

Sediment is the number one NPS pollutant in the United States (EPA, 2017a) and while NPS inputs can be continuous, most often they are intermittent and linked to seasonal agricultural activity. The flux rates of nutrients to water are influenced by factors such as season, method of application, vegetative cover, etc. but as an overall, "nutrient transport by farming systems has overwhelmed natural nutrient cycles"

(Carpenter et al., 1998). These nutrient cycles are inherently 'leaky' as when nutrient quantities in the soil are greater than what is required or present at times when not needed, they can be lost through leaching, erosion, or runoff (EPA, 2017c). All nitrogen sources can be converted into nitrate nitrogen, which is a mobile form of nitrogen, and therefore can be lost more easily from the soil (Randall & Mulla, 2001) by dissolving in surface waters or attaching to soil particles to be carried off with runoff (EPA, 2017a). Agriculture has been pegged as a major contributor of nitrate nitrogen to surface waters (Randall & Mulla, 2001).

Surface Runoff

When fertilizers are applied, generally <5% of that amount is guaranteed to be lost in runoff but this makes up only a fraction of nitrogen in surface runoff. After taking into account both infiltration and leaching, the nitrogen export from agricultural systems can range from 10-80% of fertilizer inputs depending on soil type (Carpenter et al., 1998). No matter the soil type, high percentages of the total nutrients found in runoff originated as sediment treatment (Römken, Nelson, & Mannering, 1973). Fall fertilizer application or just prior to a heavy rainfall, produced a greater loss of nitrate nitrogen into surface runoff compared to well-managed soils that significantly reduced the amount of nitrate nitrogen lost. This evaluation of nitrate nitrogen losses into surface runoff began due to more recent concerns over plant nutrient discharge, particularly in agricultural areas (Klausner, Zwerman, & Ellis, 1974).

Surface runoff occurs if the soil's maximum saturation level is exceeded, the surface depressional storage has been filled, and rainfall occurs (NSERL, 2017). This

rainfall hits the saturated ground and gets taken by gravity to flow downhill over land; as it moves, the water will flow into channels that get deposited into larger bodies of water, rivers and oceans are kept full mainly through precipitation and runoff. Roughly one-third of precipitation will become surface runoff and return to the ocean while the rest will evaporate, infiltrate, or transpire (U.S. Geological Survey, 2016). The flow rate of this excess precipitation is governed by the depth of excess precipitation, the slope of the land, and the surface roughness while the soil response to rainfall is governed by rainfall intensity, rate of infiltration, and excess precipitation runoff rate (Hawley, Jackson, & McCuen, 1983). Runoff volumes can increase with the removal of vegetation and soil (U.S. Geological Survey, 2016), as shown in Figure 4, which can increase the velocity of said runoff; lower velocity only has enough force to carry with it smaller loose particles while a higher velocity can not only carry a higher quantity, there is a force able to carry larger particles or break off more (Northern Territory Government, 2017). An increase of surface runoff can also contribute to downstream flooding and reduce groundwater recharge (Harbor, 1994). With this ability to both transport and detach large quantities of soil comes an increased rate of the associated nutrients such as nitrogen (NSERL, 2017). Although water is the most significant part of the natural process of erosion (Northern Territory Government, 2017) and even a small stream can alter course given enough time, when storms hit the increased flow and associated sediment with attached nutrients can even be seen from satellites (Perlman, 2016).

Since runoff rate is a “ratio between rain intensity and infiltration rate”, a high intensity and therefore more precipitation will yield a high runoff rate while a low infiltration rate in the soil will do the opposite (NSERL, 2017). Higher rainfall intensities

lead to a decrease of infiltration rate (Morin, & Benyamini, 1977) but forested areas have a higher rate of infiltration and less downstream flooding (Perlman, 2016). Higher infiltration rates correlate to erosion resistance due to better root systems, as with weeds, that take the precipitation further into the soil and prevent soil detachment (Podwojewski et al., 2008). Weeds and other vegetative cover increases that infiltration rate while reducing runoff velocity (Northern Territory Government, 2017) which highlights the importance of maintaining soil cover to reduce or eliminate direct impact of raindrops on soil (Morin & Benyamini, 1977).

The dominant factor in infiltration rate being crust formation, in which more crust formation leads to lowered infiltration rates (Morin & Benyamini, 1977). Precipitation that falls directly onto bare soil can break soil particles loose and cause them to block both air and water pathways into the soil (Northern Territory Government, 2017) resulting in crusted or compacted soil with a lessened ability of rainfall to penetrate to the deeper levels (NSERL, 2017). This crust has a much lower hydraulic conductivity compared to the state of the soil before, around 2-3 orders lower, with the crust accumulating before a final infiltration rate is reached (Morin & Benyamini, 1977). Crusting is more prone if there is no vegetative cover at the beginning of the rainy season or if there is a destruction of vegetative cover. Leaves both decreases the amount of precipitation that hits the soil and reduces the associated force by breaking up raindrops (Podwojewski et al., 2008).

Vegetative cover increases infiltration rates indicating that surface runoff can be directly affected by land-use. Surface runoff tends to range 5-15% per year on cultivated land compared to <5% per year under forests (Podwojewski et al., 2008) with agricultural

runoff totaling four times more than that of woodland (Harbor, 1994). The more developed a watershed is, the more runoff arrives in downstream systems at a much faster rate (Perlman, 2016) with surface losses of nitrate nitrogen also correlating to development, specifically crop, fertility level, and soil management (Klausner, Zwerman, & Ellis, 1974). Crop rotation directly affects nitrate nitrogen concentrations in surface waters (Randall & Mulla, 2001) where annual crops increase runoff, intensive annual crops cause ten times more soil detachment, but even one crop rotation after years of intense annual crops can decrease soil detachment ten times (Podwojewski et al., 2008).

Monoculture Agriculture

With a yearly addition of around 77 million people, producing an adequate food supply through agricultural practices has become challenging (CHGE, 2017). Every agricultural method will carry with it some environmental impact yet the modern, industrial agricultural methods are damaging on a next level (UCS, 2017a). The United States can comfortably be hailed as the birthplace of industrial agriculture (Rosset & Altieri, 1997) and today the majority of American farmland practices under industrial methods which were founded in the decades post-World War II and are chemically intensive. At the time, it was called a ‘technological triumph’ as it allowed the increasing population to adequately feed itself (UCS, 2017a). Post-war there was a steep decline in both the number of farms (Rosset & Altieri, 1997) and in crop diversity as today, roughly only 15 crop species supply 90% of the total food produced in the world (FAO, 2017); this diversity is critical in food production (CHGE, 2017) and a future without it leaves modern, industrial agriculture in a crisis state with most seeing it as a dead end and

unsustainable in the long-term (UCS, 2017a).

In today's modern, industrial agricultural system the practice of monoculture agriculture is widely used (CHGE, 2017) where a single crop species is produced from a field in a year, year after year (UCS, 2017b). The practice maximizes labor, which at the time was the limiting factor of production, and so any early mechanization of agriculture simply favored monoculture systems (Rosset & Altieri, 1997). This favoritism increased once it was realized that fertilizers, pesticides, and herbicides could substitute crop rotation and economic considerations made the practice widespread (Neuens & Reheul, 2001). Both political and economic forces influence the trend towards large areas of monoculture with government policies encouraging the use and businesses concentrating facilities leading to fewer, larger, more specialized farms that are capitalist intensive (Altieri, 1998). The argument that comes with the practice is that monoculture produces greater yields and grows better due to decreased pressure and uniform structure (CHGE, 2017) yet yields have begun to level off or even decrease in some areas (Rosset & Altieri, 1997). These large fields with only one crop species simplify the system (UCS, 2017b) and a lack of genetic diversity decreases stability and can increase the chance of massive crop failure (CHGE, 2017).

The US Department of Agriculture has recognized the variety of problems associated with monocropping including the use of agrochemicals (Andow, 1983). The major problem being the associated resistance factor, an overuse and dependency has led to pests and weeds needing higher doses of pesticides and herbicides to combat, if they have not yet developed resistant strains, as monocultures are more vulnerable to these factors (UCS, 2017a). Many pests and weeds thrive off of certain species, so a

monoculture of that crop acts as a more than suitable environment to breed. Pathogens also take to monocultures better with one crop allowing epidemics to be more severe, spread easier, and cause wholesale crop failure when the host plants are all uniform (CHGE, 2017). This uniformity, especially year after year, depletes the soil of the nutrients the crop species needs most and then requires an artificial replenishment that increases as years go by. Simplified systems contribute more to water pollution as there is a steady erosion from surface runoff along with the fact that much of the applied fertilizer is not utilized by the crops (UCS, 2017b).

Simplified systems also lead to a variety of problems associated with yield. Monocultures plant in rows typically but are poorly structured overall with no linkages between the crops or the crops and the surrounding land-use. Those that employ simple rotations along with monoculture systems, the narrow rotations (only one year rotation between crops) lead to a yield decrease and crops show an adverse reaction in growth if preceded by the same crop as opposed to a rotation (Nevens & Reheul, 2001). Monoculture systems also allow nutrient cycles to become more open with the addition of human introduced nutrients to the point where it is increasingly difficult to recycle nutrients (Altieri, 1998).

Agricultural BMPs

The Clean Water Act of 1972 is the primary federal law of the United States that governs water pollution; specifically, Section 404 prohibits the discharge of dredge or fill material into waters without proper permitting. However, Section 404(f)(1) outlines certain activities that are exempt from this permitting process which includes established

agricultural practices among others and therefore does not protect water pollution stemming from agricultural runoff pollution (EPA, 2017d). In response to this exemption, the United States Department of Agriculture has approached this problem in a variety of ways under their Natural Resources Conservation Service which includes the use and implementation of agricultural best management practices (USDA NRCS, 2017).

Agricultural best management practices (BMPs) are implemented on agricultural land with the intention to control erosion and improve water quality (TNDA, 2017). Specifically, management practices that permit economic and viable production with a maximum use of nutrients while also achieving the least adverse environmental impacts to preserve human, plant, and animal health. Based on the best available research, BMPs aim to minimize NPS pollution from agricultural land-use by controlling agrochemicals to reduce surface water contamination. It is possible to combine and design BMPs to protect surface waters and BMPs should be chosen to fit the entire farm operation as well as the environmental situation (Agricultural BMPs Task Force & USDA NRCS, 2002).

A major section of agricultural BMPs deal with reducing fertilizer application rates, requiring a knowledge of the soil in question; productive soils with adequate rainfall will be more flexible about fertilizer restrictions compared to poorer soils or those with less rainfall that will have a harder time adjusting (Ribaud et al., 2001). This type of management begins with soil testing, usually around the early spring time and certainly on a yearly basis, to accurately know how much nitrogen is already residing in the soil and helps make more accurate nitrogen fertilizer recommendations and a more accurate overall nitrogen budget for the farm. Setting a realistic yield, based on past data with a modest increase rather than a yield goal, accounting for other nitrogen sources like

manure, previous legumes, soil organic matter (SOM), etc., and properly accounting for crop nitrogen needs will give the most accurate nitrogen budget for a farm. This budget can help in determining the proper amount of nitrogen fertilizer needed for a growing season as overestimating yield and poor understanding of the crop species leads to excess nitrogen fertilizer application which can both cost the farmer money and adversely affect the environment. Producers can gain both economic and environmental benefits if losses of nitrate nitrogen are minimized and nitrate nitrogen uptake by the crops are maximized which correlates to the timing and application of nitrogen fertilizers (Waskon, 1994). Rather than applying the fertilizer at an arbitrary point in the growing season, timing the application to where it is most effective and needed most can reduce the amount of fertilizer that ends up in surface runoff (EPA, 2017i). Specifically, applying fertilizers as close to the period of maximum crop uptake is key and can enhance uptake of nitrogen, as past that point of maximum uptake the fertilizer will be of no more use to the plants. Different types of nitrogen fertilizers can also be used to control the amount of nitrogen that ends up in surface runoff, most fertilizers in use are nitrate fertilizers that make nitrogen readily available to the crops but is subject to intense leaching and could be improved by switching to ammonia based fertilizers that are more slow release and not subject to as much leaching (Waskon, 1994).

Agricultural BMPs also include changes in the way nutrients are managed on the field itself usually in regards to how the field is managed or the cropping practices which can total up to a 40% reduction in nitrate nitrogen losses (Ribaud et al., 2001). Controlling erosion and sediment loss of the fields can take the form of BMPs such as conservation tillage in the form of reduced or no-till, see Figure 5, along with the

utilization of cover crops. Reduced tillage indicates a plot of land will be cultivated and planted but ploughing and disking are not employed whereas no-till approaches only plant, spray, and harvest the plot of land (TNDA, 2017). Cover crops are those not planted for harvest and when planted after the main crop species has been harvested, is a BMP intended to remove excess nitrogen from the soil to reduce the amount lost in surface runoff. These types of agroecological management practices also help to build soil fertility which can reduce the leaching potential of the soil (UCS, 2017c).

Some BMPs focus their efforts away from the cropland itself and more on the surface runoff that inevitably comes off, with this main focus being filtering said surface runoff to remove nutrients before they can reach downstream systems. Close to the cropland itself are the option of filter strips, or riparian buffers, which are long, narrow vegetation strips usually planted between fields and streams which slow surface runoff rate and allows the nutrients in the runoff to settle out and not reach the body of water; a basic implementation can be seen in Figure 6. This is a very similar practice to managing bank vegetation, where stream or river banks are kept full of vegetation to filter out nutrients from runoff, but bank vegetation management can be done along the entirety of the stream or river and intended more to combat NPS pollution than that from a certain farm (TNDA, 2017). While these buffers do work to naturally filter N from the runoff water, wetlands have a greater capacity to do so. By employing wetlands around agricultural land, runoff can be processed through here and trap nitrogen contained in the runoff before processing it through plant uptake or denitrification (Ribaudó et al., 2001).

Polyculture Agriculture

There has been growing concerns about intensive agriculture (monocultures) and the ability to maintain them long-term (Matson et al., 1997) which raises the challenge of finding an alternative. Polycultures are an alternative approach to farming that “rejects the inevitability of agriculture running down its natural resources” (Lefroy & Hobbs, 1998) that are a synthesis of a natural system, as natural ecosystems are the supreme farmer and are unmatched in nutrient cycling but cannot sustain dense populations in terms of food (Cox, Picone, & Jackson, 2004). In 1978 there was an argument by Wes Jackson for agriculture to be based on the way nature works (Jackson, 2002) as these natural systems have fed much of the world for centuries and still do in some countries such that around 20% of the world food supply is still grown in polycultures (Altieri, 2009). Polycultures are quite common in small, subsistence agricultural areas around the world in most ecosystems and true polycultures can have upwards of 30 species on a given plot of land when taking into account trees, livestock, and fish (Dewar, 2007).

This more ecologically complex cropping system (Ghazali et al., 2016) attempts to increase food production while preserving the natural resource base (Altieri, 1999) so conservation is a consequence and not just an afterthought (Lefroy & Hobbs, 1998). This setup does require greater management intensity (Hanson et al., 2007) but provides greater crop diversity, sequence flexibility, and meets agronomic, economic, and environmental objectives (Iverson et al., 2014). Polycultures do not attempt to radically modify traditional and local farming systems, but rather optimize their designs (Altieri, Funes-Monzote, & Petersen, 2011). This blended idea of modern agroecological science and indigenous knowledge revolves around the standard of having two or more crop

species occupying the same space and time which can be branched off into a variety of types (Altieri, 2009). These can focus on increasing yield (intercropping, multi-cropping, alley cropping) or decreasing pests or soil degradation (companion planting, beneficial weeds) as different species of crops fill different roles and have different needs in terms of nutrients, water, light, etc. (Jackson, 2002).

Polycultures can have the positive effect of reducing the nutrient needs of a plot of land by adapting traditional farming systems that have been shown to be ideal candidates for nutrient cycles. As these systems were much better at cycling nutrients without the interference of human-introduced sources, any adaptation would optimize the nutrient cycling of the given plot of cropland (Altieri, 1999) and a basic cycling of this can be seen in Figure 7. Traditional farms used legumes to offset the nitrogen needs of the subsequent crops, as they are nitrogen-fixing crops that do not need an external input of nitrogen, to both supply nitrogen to subsequent crops and reduce leaching by way of sequestering nitrogen. Vegetable crops have little capacity for recovering soil nitrogen due to their shallow root systems and extra steps must be taken to reduce the risk of nitrate nitrogen loss, legume-based systems can both increase subsequent nitrogen uptake by vegetable crops and reduce nitrate leaching leading to upwards of a 40% leaching reduction relative to fertilizer application. Polycultures in general are more effective at sequestering nitrogen due to an increase in total root mass (Treadwell, 2006), decreasing the distance between crops and trees increases the soil nutrient concentration (Altieri & Trujillo, 1987), intercropping has been shown to have a greater nutrient uptake (Singh et al., n.d.) and there is some indirect evidence that supports perennial polyculture has the ability to support its own nitrogen needs entirely (Jackson, 2002).

Traditional cropping systems should also be adapted on the basis of their productivity which can translate over to modern croplands. More complex cropping systems are reasonably productive, considering the land limitations most work under along with the low external inputs of nutrients (Altieri, 1999), with a 50-100% increase in production usually found in alternative cropping systems compared to monocultures (Altieri, Funes-Monzote, & Petersen, 2011). Complex mixtures and increased crop biodiversity maximize more ecosystem functions at the same time improving the overall system yield due to species interaction, where one or a few production species influence the rest in kind (Picasso et al., 2008). Integrating trees can also positively influence growth and yield along the same path as it influences the cropland regarding soil nutrient concentration and certain trees affect crop yield more than others depending on crop species (Altieri & Trujillo, 1987). Crop biodiversity could also provide a link between stress and resilience as in most complex cropping systems, the biodiversity provides insurance to the producer. Not only can it protect against human factors (Lin, 2011) but also environmental ones like disasters (Trujillo-Arriaga & Altieri, 1990), climatic conditions, and ecosystem functions (Treadwell, 2006).

Traditional cropping systems have been shown to be less vulnerable to catastrophic loss along with the associated modern adaption of polycultures (Altieri, 2009) and may provide a productive solution to building resilience in agricultural systems (Lin, 2011). In the aftermath of Hurricane Mitch, Altieri, Funes-Monzote, & Petersen (2011) found that an American hillside where diversification was present suffered less damage compared to neighboring more simple systems. Not only does an increase in crop diversity strengthen ecosystem stability (Picasso et al., 2008), it also has been shown to

use resources more efficiently (Lithourgidis et al., 2011) with polyculture use of resources more intense than that of simpler systems (Trujillo-Arriaga & Altieri, 1990). Along with this, polycultures contain higher animal biodiversity and do better in the protection of farmland animal biodiversity (Ghazali et al., 2016) with the ability to increase soil conservation and soil fertility (Lithourgidis et al., 2011). An increase in crop diversity also decreases pests, weeds, and diseases (Singh et al., n.d.). The complex systems reduce the number of pests and weeds as most species of these are associated with specific crop species and so a variety of such will not only reduce the attraction rate but also attract natural predators to both pests and weeds from other crop species (Picasso et al., 2008). Diseases are also not as likely to cause widespread crop failure, as with pests and weeds most diseases are specific to certain crop species and a variety does not allow the disease to travel well (Hanson et al., 2007). In imitating nature, these more complex systems should eliminate ecological degradation and minimize the need for human interaction (Jackson, 2002).

Comparison

There happens to be a mistaken belief that monocultures yield better compared to diverse cropping systems, so there is an importance of highlighting the difference between the two in terms of yield but also in other regards as yield should not determine success rates. These benefits beyond yield include studies showing maize grown in polycultures result in better insect, pest, and soil fertility management (Altieri & Trujillo, 1987) along with improved root growth and root vigor (Nevens & Reheul, 2001). Looking at an American hillside post-Hurricane Mitch, diverse cropping systems suffered

less damage when compared to their monoculture neighbors. This observation was also seen in Cuba after Hurricane Ike, where there were 50% losses in polyculture systems compared to 90-100% losses in monoculture systems; polyculture systems also showed a faster recovery time in the 40 days after the hurricane (Altieri, Funes-Monzote, & Petersen, 2011).

Moving into yield comparisons, controlled studies show that polycultures on fertile soils with highly productive forage species typically averaged higher yields compared to monocultures or less diverse systems under the same conditions (Picasso et al., 2008). Many crop species have been shown to increase yield when compared to monocultures of the same focus crop species; cereal and legume intercropping (Fujita, Oforu-Budu, & Ogata 1992), integration of velvet bean into maize (Altieri, Funes-Monzote, & Petersen, 2011), maize in general (Neuens & Reheul, 2001), and typical polycultures (Trujillo-Arriaga & Altieri, 1990). Maize on its own has also shown great promise in nullifying monoculture effects on cereal species or soybeans (Neuens & Reheul, 2001). A meta-analysis of ecological research show that on average, yields from diverse polyculture systems do not differ from the best yielding monocultures and in some instances even outperform them (Picasso et al., 2008).

Looking into nitrogen loading, monocultures with the typical row systems produce higher runoff volumes and nitrate nitrogen losses from these range from 30 to 50 times higher than from polycultures (Randall & Mulla, 2001). Poudel et al. (2001) describes a ten-year study looking into the impacts of cropping systems on soil nitrogen storage and loss with an organic system compared against conventional monocultures where the organic system had a mixture of crop species and no input of chemical

fertilizers. The organic system compared against the conventional systems showed the highest cumulative nitrogen input and nitrogen balance as well as the least nitrogen output; the system also accumulated the greatest amount of nitrogen which was being stored in the soil rather than being lost which can be seen occurring in Figure 8. Diekow et al. (2005) looked into a seventeen year study on cropping systems, nitrogen fertilization, and their effects on soil nitrogen stocks comparing two intercropping systems against one that practiced sequential cropping. The legume-based systems in both intercrops showed significantly increased soil nitrogen stocks and by the end of the study, the two intercrops had achieved the original nitrogen stock of the native grassland of the area in the topsoil layer.

Recommendations

These principles of sustainable agriculture through polycultures are applicable to any food production system worldwide (Cox, Picone, & Jackson, 2004) and are compatible with modern agriculture, especially under environmentally stressed conditions (Trujillo-Arriaga & Altieri, 1990). Certain varieties of polyculture have gained notoriety in dryland agriculture, compared to irrigated agriculture, for precisely the practice's resilience in the face of environmental stress (Singh et al., n.d.); polycultures have exhibited greater yield stability and less productivity declines in the face of a drought compared to monocultures with intercrops overyielding consistently at five different levels of moisture availability and this rate of overyielding actually increasing with water stress (Altieri, 2009). Even in intensively harvested agroecosystems, species-rich polycultures should be considered (Picasso et al., 2008).

There is no vision of the future where polycultures will eventually replace all annual monocultures but as the practice is so highly applicable the effort should be made where possible and practical. Polycultures are plausible in rainforest, temperate forest, grassland, and chaparral ecosystems which encompasses nearly all of the world's land currently under significant cultivation, see Figure 9. Advocates argue that replacing annual monocultures on marginal land and highly erodible soil would make sense, which in the United States would encompass 350 million acres of the 400 million total tillable acres as these are classified as mildly to highly erodible soil (Dewar, 2007).

A majority of the BMPs suggested for nitrogen fertilization focus on continuing monoculture practices albeit with reduced negative effects; conservation tillage, assessing nitrogen demands, and scheduling fertilizer all can be applied to farmlands without switching away from monoculture practices. Constructing filter strips and planting bank vegetation also do not require a change of agricultural practices away from monoculture. Polyculture, however, does require a shift away from monoculture while still getting the benefits of reduced negative environmental effects by reducing the nitrogen demand through crop diversity or reducing the transfer of nitrogen into surface runoff through root systems and minimizing bare soil. While BMPs are a good stepping stone away from monoculture, polyculture should be the ultimate stage of sustainable agriculture. Those farms that have already employed BMPs should make the transition towards polyculture practices as well as farms with less space where crop diversity can maximize available space. Farmers should also look into the benefits that multiple crop production and reduced demand for pesticides, herbicides, and fertilizers can do for a farm's net profit.

Limitations of Adoption and Study

Although polyculture practices have been around far longer than monoculture practices, since the industrial agricultural boom in the recent decades it has been difficult to adopt back those diversification processes. These decades have taught scientists the ‘law of the minimum’ where at any moment there is a single limiting factor to production that can be solved but leads to a cycle of solving each new limiting factor that occurs from solving a previous; also known as ‘Liebig’s Law’, it can best be conceptualized with a barrel analogy, like the one found in Figure 10. These solutions come in the form of fertilizers, pesticides, etc. to treat nitrogen deficiency, pests, etc. which do nothing except treat symptoms of a larger ecological unbalance and leave in place a key factor of the agricultural crisis, that of extensive monoculture practices (Rosset & Altieri, 1997). In modern agriculture, economic policies and mistaken beliefs of yield do nothing but bolster the practices of monoculture instead of shifting towards a more sustainable process. Economic policy incentives towards monocultures far outweigh any perceived incentives of diversification; agricultural subsidies are geared towards a select few crop species and commodity payments are distributed based on acreage of crop produced both of which incentivize maximum production of a few crop species over a larger area (Lin, 2011). The capital-intensive modern farming practices make the system dependent on suppliers of inputs which carries with it immense profits and this potential profit loss from a move to alternative cropping systems leaves the agrarian system resistant to change (Rosset & Altieri, 1997).

Diversified systems have been largely absent from modern agriculture due to the mistaken belief that biomass production is greatest in monoculture systems compared to

diversified ones. With the goal of agriculture being high yield in order to supply the food demand, annuals have been favored as these crop species focus their energies on producing seeds whereas perennial species focus more of their efforts on root systems (Dewar, 2007). Although monocultures work at a much-reduced capacity compared to that of polycultures, the use of external inputs such as chemical inputs, mechanization, irrigation systems, etc. can replace the lost functionality while also promoting higher yields. These external inputs are also easier to gear towards one crop species which only adds to the favoritism of monocultures (Lin, 2011).

Along with the agricultural industry favoring monoculture practices, farmers also play a hand in the adoption of diversified agriculture. In general, this adoption could be bolstered if farmers were better informed on the effects of the monoculture practices and had better ideas and plans to optimize production and profits of diversified systems (Lin, 2011). In Robinson & Napier (2002), older farmers (40s) located in Ohio, Iowa, and Minnesota were asked about chemical inputs on their croplands; the mean response showed that the farmers had both a low perceived risk of farm chemicals to the environment as well as a low perceived impact of farm chemicals on water quality. A meta-analysis of factors influencing BMP adoption showed age to be a significant negative impact on the adoption of BMPs which suggests that older farmers may have a shorter planning horizon and different approaches would need to be looked into to overcome this factor (Baumgart-Getz, Prokopy, & Floress, 2012).

While these diversification adoption factors focus on a single social or economic force, this study focused on a single ecological force, that of nitrogen loading from agricultural lands increasing hypoxia in downstream ecosystems. In all cases, however,

any alternative attempting to solve the agricultural crisis must address ecological, social, and economic forces in conjunction as focusing entirely on one would spell disaster. The case of agriculture has ecological and socioeconomic dimensions and without addressing all of them the overarching factor fueling the crisis cannot be appropriately addressed without causing more issues (Rosset & Altieri, 1997). It comes down to research agendas, policies, institutions, and development agendas needing be reformed (Altieri, Funes-Monzote, & Petersen, 2011) in order to massively adopt agroecological alternatives so their full benefit of sustainable food security can be both realized and utilized in the wake of a changing tomorrow.

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APPENDIX

Eutrophic and Hypoxic Coastal Areas of North America and the Caribbean

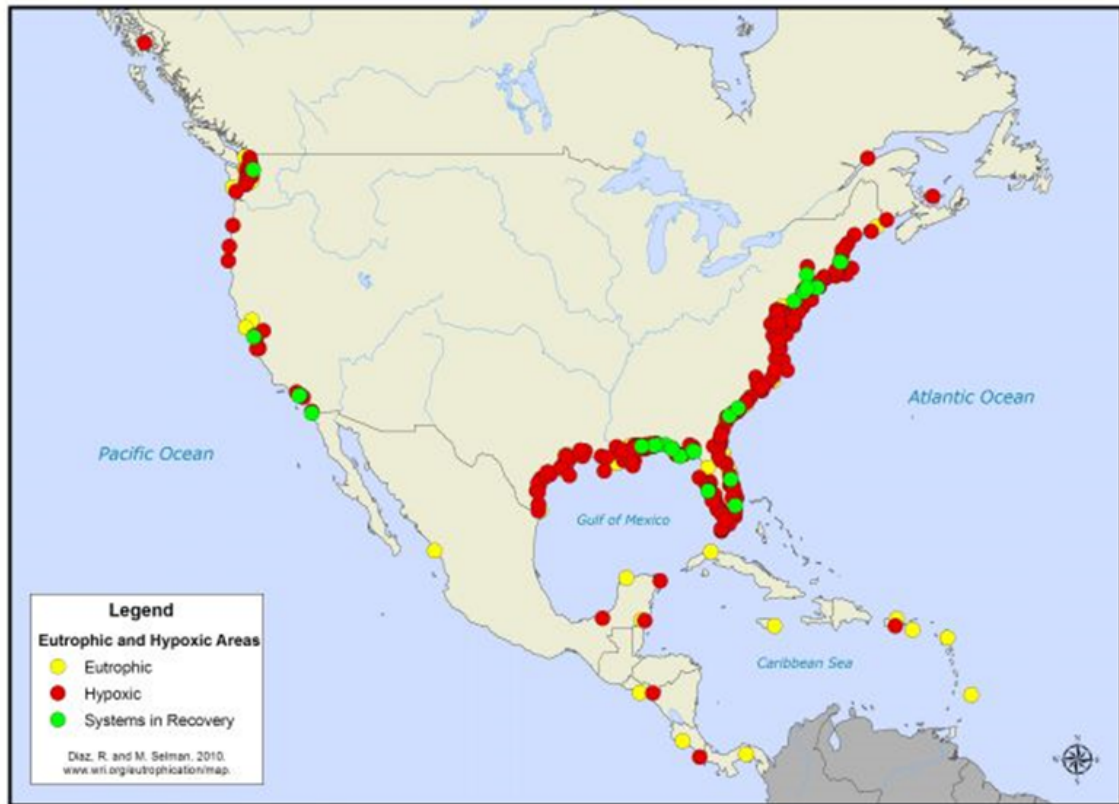


Figure 1: A map of the North and Central America sourced from data in 2010 which showcases areas that either eutrophic, hypoxic, or those systems currently in recovery from these afflictions. Sourced from wri.org

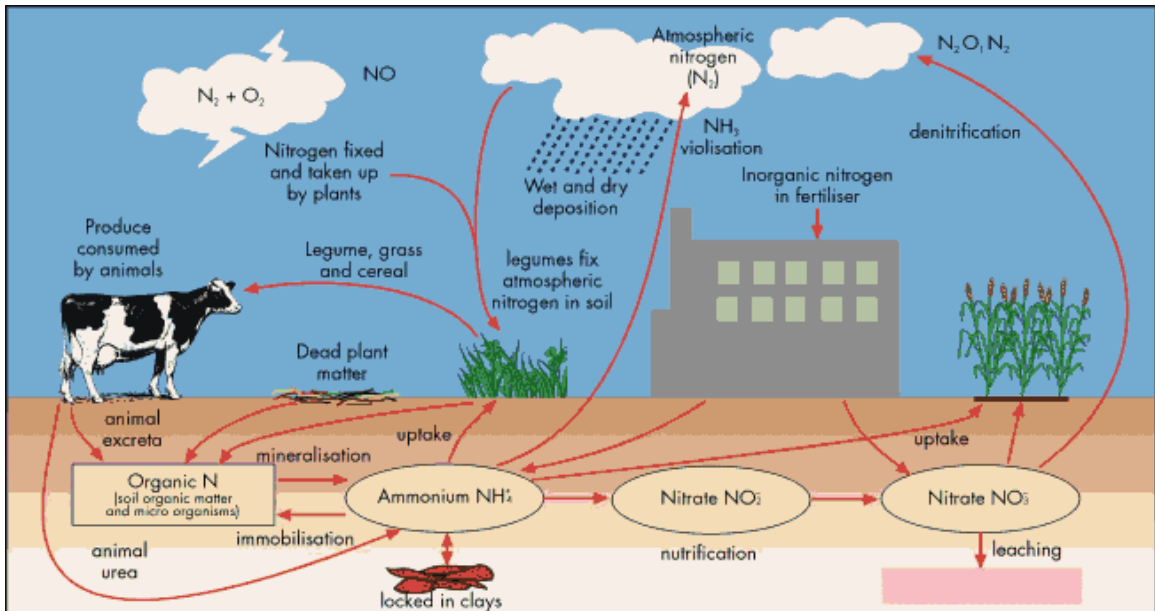


Figure 2: An information graphic to showcase the nitrogen cycle and the different interconnected inputs and outputs which include anthropogenic, atmospheric, agricultural, etc. sources. Note that the nitrogen being leached from the cycle is in the form of nitrate nitrogen and comes from various sources within the cycle. Sourced from snh.gov.uk

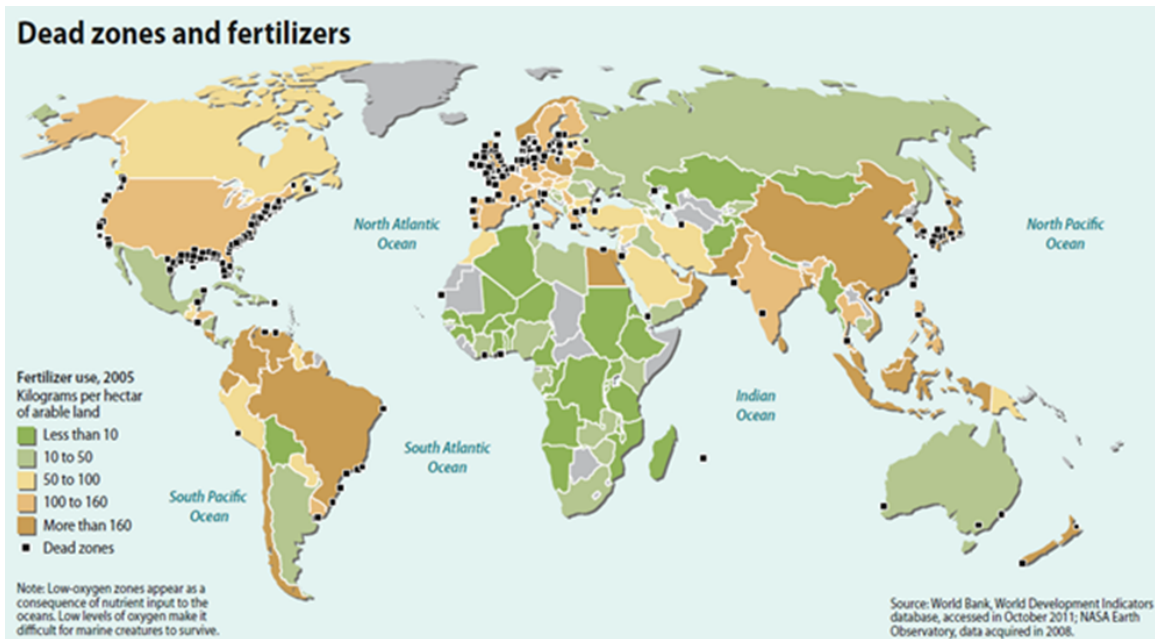


Figure 3: World map with data sourced from the World Development Indicators database and NASA Earth Observatory in 2011 and 2008 respectively which shows the correlation between fertilizer use and dead zones. Note that those countries that use more fertilizer per hectare of arable land, more orange in color, see more dead zones, black squares, along their coastlines. Sourced from World Bank

PERCENTAGE (%) OF SURFACE RUNOFF ON A VARIETY OF SURFACES

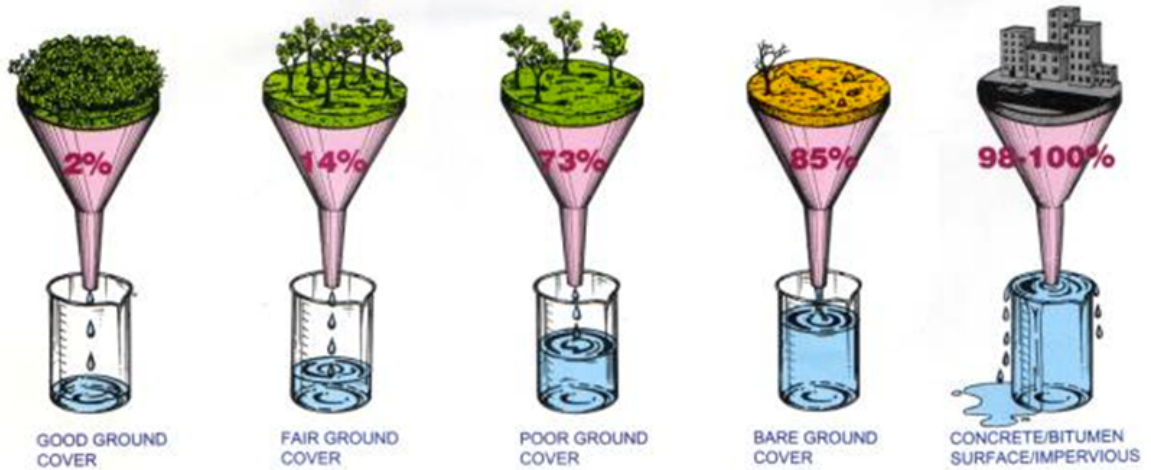


Figure 4: A simple graphic showcasing different land uses and their impact on the percentage of surface runoff. Sourced from igeogers.weebly.com

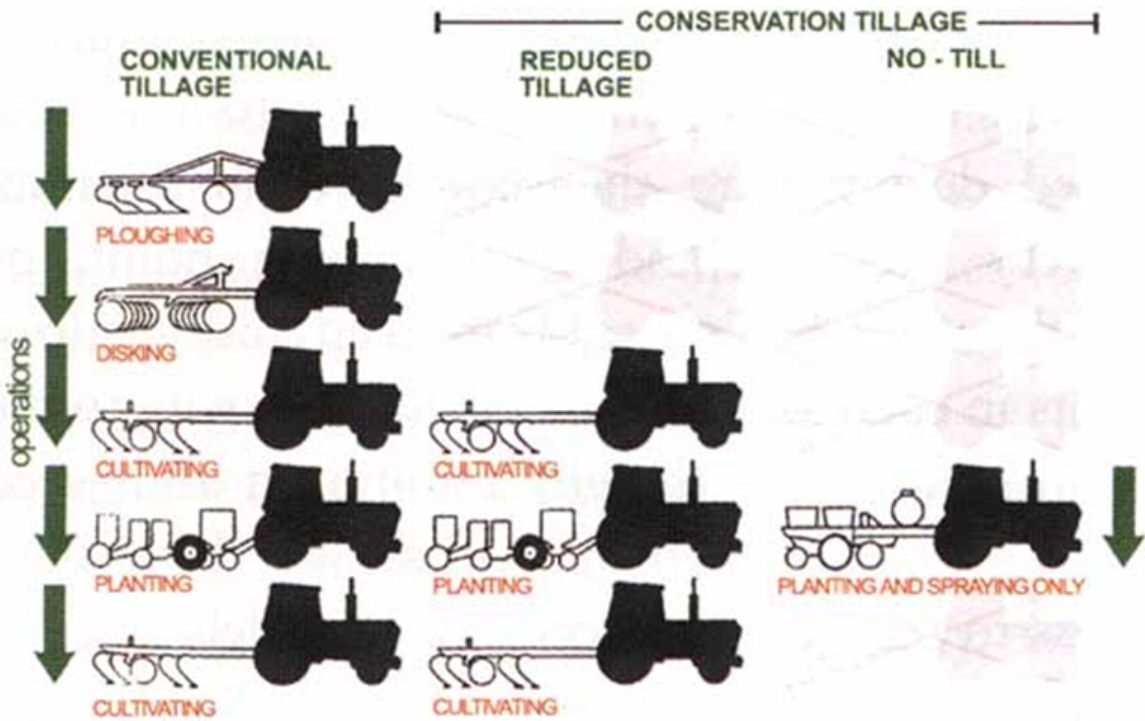


Figure 5: Graphic showing the differences between two types of conservation tillage and conventional tillage in terms of the practices employed. Sourced from fao.org

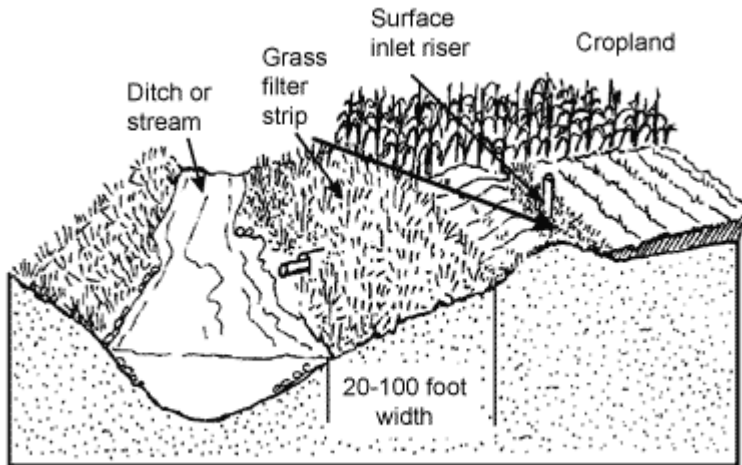


Figure 6: A simple concept of implementing a filter strip between cropland and a stream in order to filter the agricultural runoff. Sourced from agry.purdue.edu

Legume based cropping system

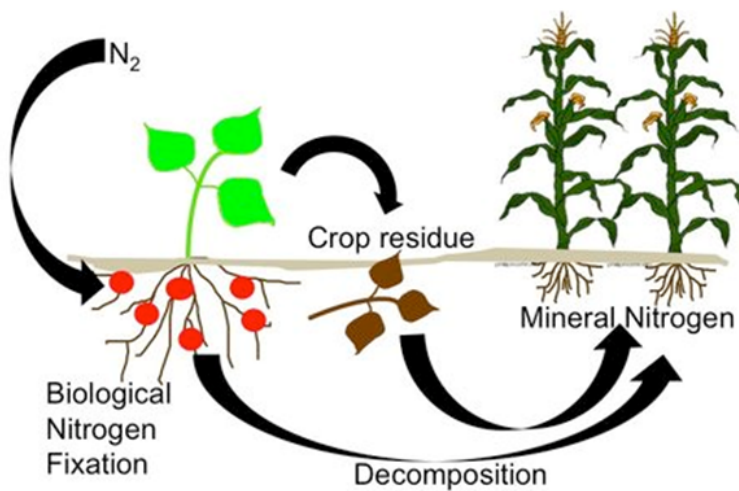


Figure 7: A basic graphic to showcase the cycling of nitrogen that can be found in a legume based cropping system in which the legume crops fix their own nitrogen and can then supply nitrogen to non-nitrogen fixing crops such as corn. Sourced from holisticmanagement.ca

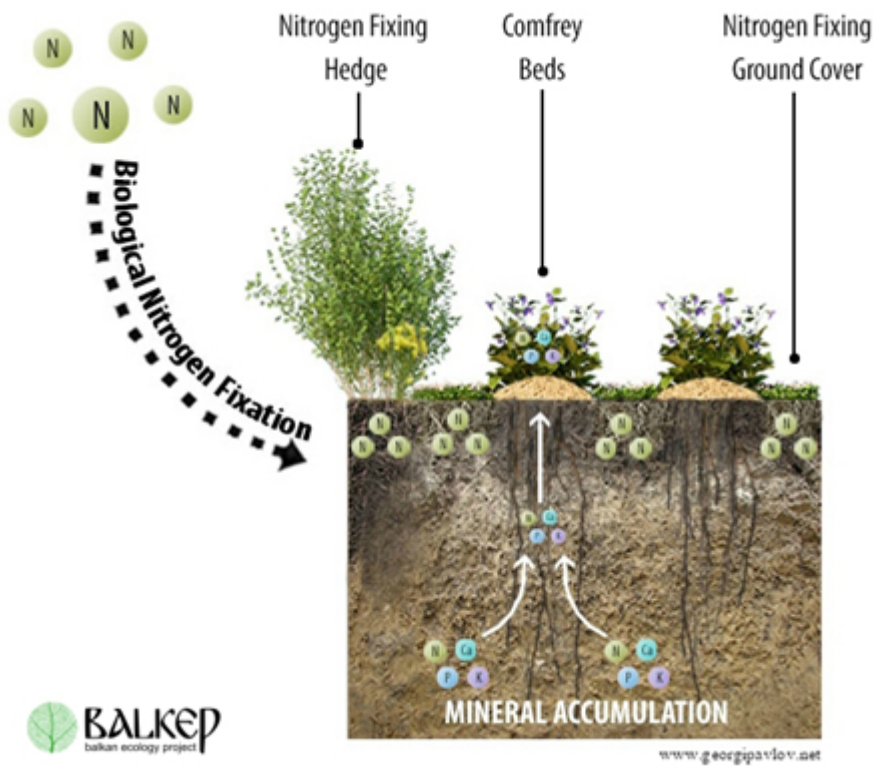


Figure 8: A polyculture system diagram that shows how nitrogen gets collected in the soil of the system rather than in the subsequent runoff. Sourced from permaculturenews.org

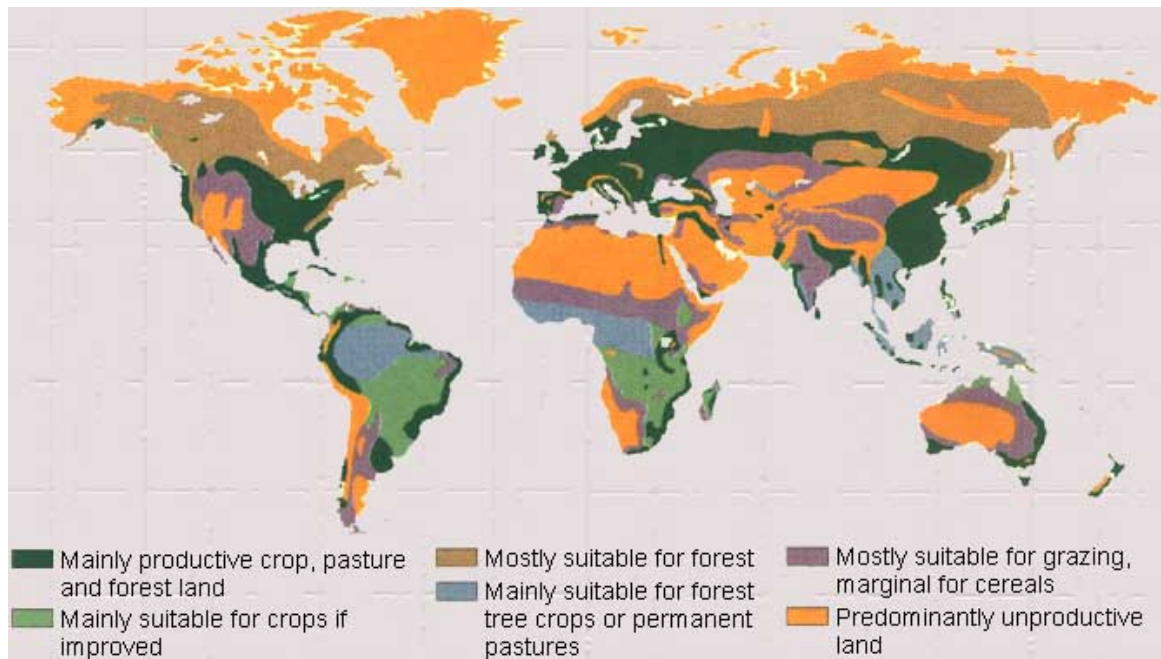


Figure 9: A world map that color codes the land into different land uses, not as they are currently used but rather as what they could be used for given their current soil type. Sourced from fao.org

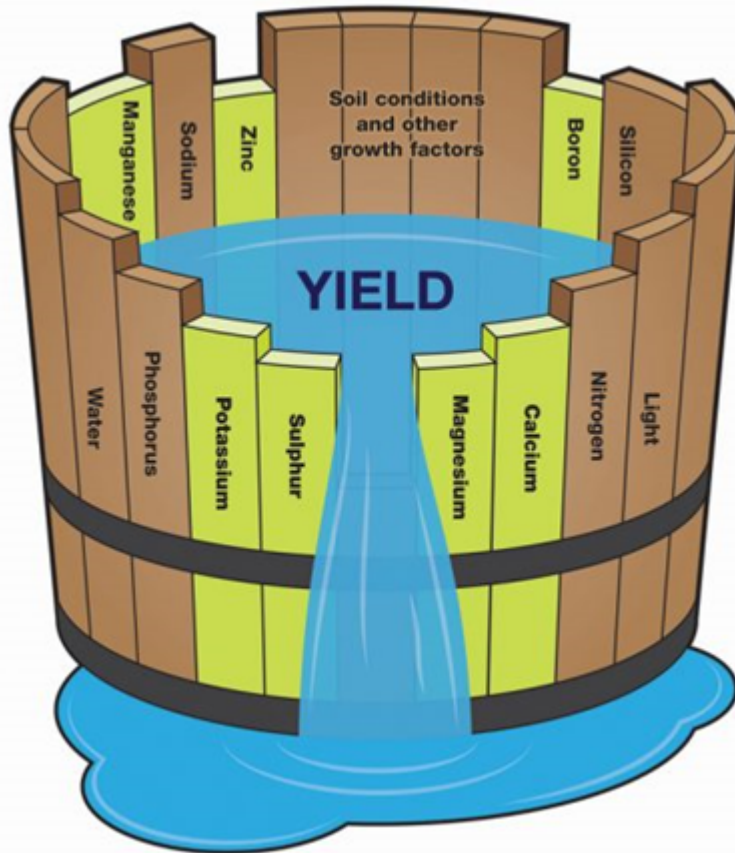


Figure 10: A basic graphic showing the barrel analogy typically used to explain the Liebig's Law of the Minimum; each nutrient and factor of crop production has a different length and so each will cause the yield to decrease until the absolute minimum yield is reached. Sourced from fertilizer-thai.com

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Bethany M. Stevens was born in Clarks Summit, Pennsylvania on April 4, 1995. She graduated from Abington Heights High School in 2013 as part of the National Honor Society; as a lifetime Girl Scout, she completed her Gold Award in 2013. Majoring in marine science, she studied abroad at Griffith University in Brisbane, Australia her junior year. She is a member of Phi Sigma Pi National Honor Fraternity and has received the University of Maine Dean's Scholarship and the Maine Sea Grant Undergraduate Scholarship in Marine Science.

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