Managing Nutrients for Plants and Water Quality

The science behind plant nutrient needs and how water quality can be impacted and protected by nutrient management and context-appropriate practices

Franklin County Natural Resources Conservation District, St. Albans, Vermont

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Introduction

Managing nutrients with informed planning can help land stewards with plant production, reducing water resource pollution, protecting air quality, budgeting costs, and improving soil health conditions. The goals of this paper are to provide the general public with a basic scientific understanding of the nutrient needs of plants, a description of why nutrients (in the forms of amendments like manure, fertilizers, composts, or other materials) are applied to the land, a brief explanation of how poor nutrient management can lead to water quality issues, and what can be done at various scales to mitigate those issues. Though these ideas are most often focused on agricultural lands, they apply in the same way to backyards, urban areas, forests, and other landscapes.

How Do Plants Grow?

Plants, like everything else in the universe, are made up of combinations of atoms of various elements in patterns and structures that give them their unique appearances and characteristics.

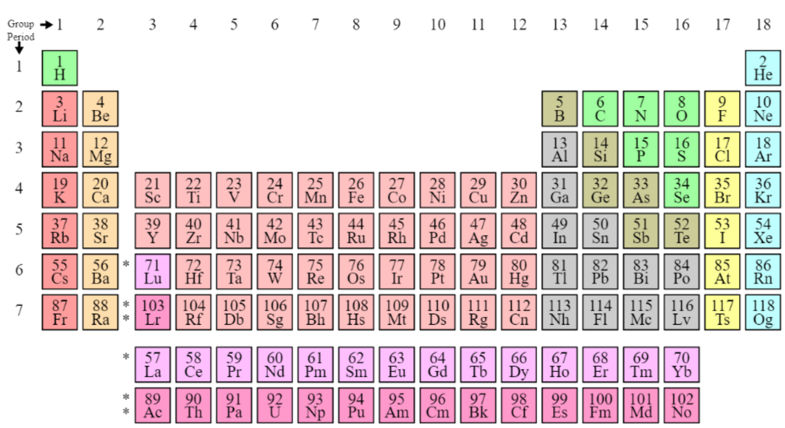

Fig 1. Periodic Table of Elements

Science Class Refresher:
Remember learning about the Periodic Table of Elements (Fig 1.)? The Periodic Table shows all the known elements like carbon, phosphorus, hydrogen, nitrogen, potassium, calcium, and zinc, as examples. These elements are defined by the number of protons (positively charged particles) in their atoms - so the number of protons in a carbon atom (6 protons) is different than the number of protons in, say, a phosphorus atom (15 protons).

Atoms also have neutrons (uncharged particles - not positive or negative) and electrons (negatively charged particles). The number of electrons can vary; it is not set in stone like protons are for each element. This is important because this means that an atom, or a combination of atoms — called a "molecule" — can have an overall net positive or negative charge based on how many electrons it has. An atom or molecule with a net charge is called an "ion". An ion with a net positive charge is called a "cation" (more protons than electrons); an ion with a net negative charge is called an "anion" (more electrons than protons).

Additionally, even a molecule with the same number of protons and electrons can have a difference in charge on each side depending on where those electrons are in the structure of the molecule. One side of it might have a slightly positive charge and the other side might have a slightly negative charge. These molecules are called "polar" molecules — water (H_2O) is a common and important example of a polar molecule (Fig. 2).

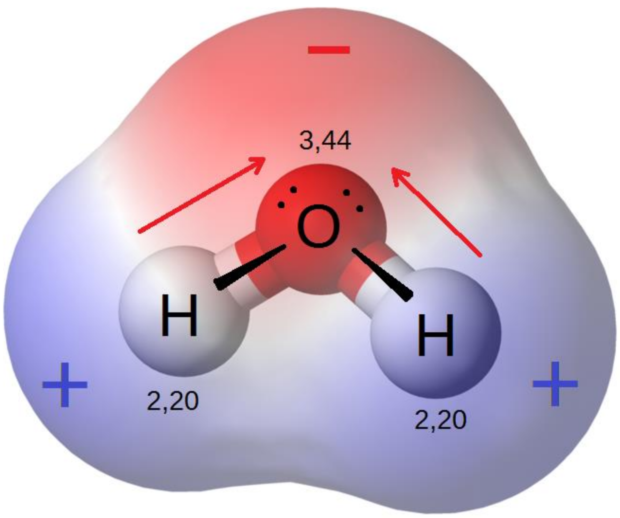

Fig. 2. Water is a polar molecule, with a slight positive charge at the hydrogen end and a slight negative charge at the oxygen end. Image source: Riccardo Rovinetti via Creative Commons.

All of this matters because the overall net charge of the molecule and the arrangement of the electrons can immensely impact if that molecule can be used by plants, held by soil particles, or dissolve in water.

Nutrients

All living things require certain elements in order to function and grow. These elements are often referred to as "nutrients" — this is especially common when talking about plants. Nutrient elements, such as nitrogen, phosphorus, and potassium, make up plant DNA, proteins, and the other chemical building blocks of plant tissues.

Nutrients can be found naturally in the soil, in the air, in the water, in old plant material or animal waste, or in fertilizers made by humans – everywhere! However, most of the time, nutrients do not exist in the environment as single atoms. Nutrients are usually part of larger, more complex molecules with a combination of different elements, which can sometimes cause confusion.

Plant Available Forms of Nutrients

Importantly, plants and soil microbes can only use nutrients in certain forms - molecules and ions that are structured in particular ways that plants can absorb and use efficiently to perform their life cycle processes like photosynthesis, which enables plants to grow.

Plants need molecules and ions that contain atoms of eighteen different elements (nutrients) in particular combinations, called "plant available forms" (Table 1). Plants require the elements carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur in relatively larger quantities, so these elements are referred to as "macronutrients". The other plant essential elements – iron, manganese, boron, molybdenum, copper, zinc, chlorine, nickel, and cobalt – are found in much lower concentrations in plant tissue, so they are sometimes referred to as "micronutrients".

*Table 1. Nutrients and their plant available forms. Macronutrients are shown in **bold**.*

Nutrients	*Plant available form(s) Molecule formula (Name)*	*How it is lost to the environment or otherwise plant unavailable*	*Process used by plant*
Carbon	CO_2 (Carbon Dioxide)	N/A	Plant growth, glucose for plant energy, respiration[3]
Hydrogen	H^+ (Hydrogen Ion) OH^- (Hydroxide)	N/A	Photosynthesis, respiration, glucose for plant energy, aid in proton gradients to help drive electron transport chain in photosynthesis and respiration[3]
Oxygen	O_2 (Dioxygen)	N/A	Respiration, photosynthesis[3]
Nitrogen	NH_4^+ (Ammonium) NO_3^- (Nitrate)	Leaching, Volatilization, Denitrification, Runoff and Erosion[1]	Proteins, protoplasts, enzymes, chlorophyll synthesis, photosynthesis[2, 3]
Phosphorus	HPO_4^{-2} (Hydrogen Phosphate) $H_2PO_4^-$ (Dihydrogen phosphate) Both are part of a group known as "orthophosphates"	Binds (precipitates) to aluminum, iron, manganese, or calcium (depends on pH) Runoff and Erosion Leaching[1]	ATP, ADP, basal metabolism, root development and early seedling growth[2, 3]
Potassium	K^+ (Potassium Ion)	Leaching Runoff[1]	Water relations, energy relations, cold hardiness, enhances enzyme actions aiding in photosynthesis and food formation, builds cellulose, helps translocate sugars and starches, improve drought tolerance[2, 3]
Calcium	Ca^{2+} (Calcium Ion)	Leaching Runoff[1]	Cell structure, cell division, cell elongation, balance organic acids, activates several plant enzyme systems, improve root growth conditions and stimulating microbial activity and affects uptake and availability of other nutrients, stimulates root and leaf development[2, 3]
Magnesium	Mg^{2+} (Magnesium Ion)	Leaching Removal by plants[1]	Chlorophyll, enzymes, photosynthesis, phosphorus carrier[2, 3]

Sulfur	SO_4^{-2} (Sulfate)	Leaching Erosion Removal by plants[1]	Proteins, protoplasts, enzymes, photosynthesis, winter crop hardiness, chlorophyll formation, seed production, Legume need S for efficient nitrogen fixation[2, 3]
Iron	Fe^{2+} (Ferrous ion) Fe^{3+} (Ferric ion)	Leaching Oxidation to insoluble mineral forms	Chlorophyll synthesis, metabolism, enzyme activation, nitrogen reduction and fixation, lignin formation, carries oxygen in the nodules of legume roots[2, 3]
Manganese	Mn^{2+} (Manganese 2+) Mn^{4+} (Manganese 4+)	pH-dependent binding to soil minerals and organic matter	Chlorophyll synthesis, enzyme activation, accelerates germination and maturity[2,3]
Boron	H_3BO_3 (Boric acid) $H_2BO_3^-$ (Dihydrogen borate)	Leaching[1]	Sugar translocation, cell development, growth regulators, seed set, nitrogen fixation in legumes[2]
Molybdenum	MoO_4^{-2} (Molybdate ion)	Leaching	Nitrogen fixation in legumes, nitrogen use[2]
Copper	Cu^{2+} (Cupric ion)	pH-dependent binding to soil minerals and organic matter	Enzyme activation, chlorophyll formation, catalyzes plant reactions[2]
Zinc	Zn^{2+} (Zinc ion)	pH-dependent binding to soil minerals and organic matter	Protein breakdown, enzyme activation, protein synthesis, growth regulation[2, 3]
Chlorine	Cl^- (Chloride ion)	Leaching	Photosynthesis, stomatal regulation, involved in chemical breakdown of water in the presence of sunlight and activates several enzyme systems, acclimate to changing water availability, transport of nutrients within a plant[2, 3]
Nickel	Ni^{+2} (Nickel ion)	pH-dependent binding to soil minerals	Iron metabolism, Nitrogen metabolism[2]
Cobalt	Co^{2+} (Cobalt (II) ion)	pH-dependent binding to soil minerals	Nitrogen fixation occurring within the nodules of legume plants[4]

Table 1 References:
(1) Darby, Heather. 2009. *Digging In: A Nutrient Management Course for Farmers*. University of Vermont Extension. Northwest Crops and Soils Program.
https://www.uvm.edu/sites/default/files/media/DiggingIn2017_Final_ReducedSize.pdf
(2) Maher, Robert. 2004. *Nutrients Plants Require for Growth*. University of Idaho Extension. Idaho Agricultural Experiment Station. CIS 1124.
https://www.extension.uidaho.edu/publishing/pdf/CIS/CIS1124.pdf
(3) The Mosaic Company. 2021. *Nutrient Knowledge.* https://www.cropnutrition.com/nutrient-knowledge Accessed 11/26/2021
(4) International Plant Nutrition Institute. *Nutri-Facts- Agronomic fact sheets on crop nutrients: Cobalt.* Ref. #15 #15049 https://www.ipni.net/publication/nutrifacts-na.nsf/0/5D2097137F73C07F85257EA8006297B0/$FILE/NutriFacts-NA-15.pdf

As Table 1 shows, a lot of the plant available forms of nutrients are positively or negatively charged ions. These ions can attach to water molecules, which have both negatively and positively charged sides because they are polar molecules (see Fig. 2). Like a magnet, the negative side of an ion will attach to the positive side of the water molecule, and vice versa. Once “dissolved” in water, or attached to a water molecule, plant roots can absorb the combination of ions and water; those nutrients then become available to the plant to use in its life cycle processes - like building its body, helping with photosynthesis, and reproduction. When plant tissues die, they return to the soil as organic matter, which can be digested by soil microbes to release the nutrients within, in a process called “nutrient cycling”.

Nutrient Imbalances on the Landscape

Landscapes and soils can have nutrient imbalances caused by natural soil chemistry, limited nutrient cycling, removal of nutrients through harvest, leaf removal, lawn cutting removal, or by overapplication of nutrients when adding too much of a fertilizer or other amendment. When humans get involved in this cycle of nutrients on the landscape, large amounts of nutrients can be moved over vast swaths of land. This can be beneficial if it involves bringing nutrients back to a degraded landscape as amendments or if it entails bringing food to feed hungry people in areas where food is difficult to grow. This can be harmful if it involves bringing too many nutrients to one area through overapplication because the nutrients might negatively affect the soil, water, and air.

To account for nutrient imbalances on landscapes managed by humans such as farms, gardens, lawns, recreation fields, and other areas, nutrients are often added back to the land to help plants and microscopic organisms in the soil (microbes) grow. Nutrients are applied through amendments such as manure, compost, fertilizer (organic and synthetic), biological products containing organisms, and others. Through amendment application, nutrients that were previously removed as plant material (corn stalks, hay, leaves, grass) can be replenished in efforts to rebalance nutrient cycles and support plant growth.

Ion Exchange Capacities and pH

The nutrients that are either naturally occurring and cycling in the local soils or added through human management are held in the soil for use by plants and other living organisms. These nutrients, in plant available forms, are found in the soil around roots; different soils hold onto the nutrients with different "strengths". For example, soils that have clay particles or organic matter (like decomposed plants, leaves, compost, manure, etc.) are negatively charged; clay and organic matter are made up of molecules with overall negative charges. These negatively charged soils attract and hold tightly onto nutrients that are held in positively charged ions (cations) because opposites attract. The ability of a soil to hold onto these positively charged ions is called "cation exchange capacity (CEC)" - the higher the CEC, the better the soil is at holding onto positively charged nutrients, some of which growing plants can use (Fig. 3). Sandy soils typically do not have high CECs, but CECs can be increased by building up the amount of organic matter in the soil.

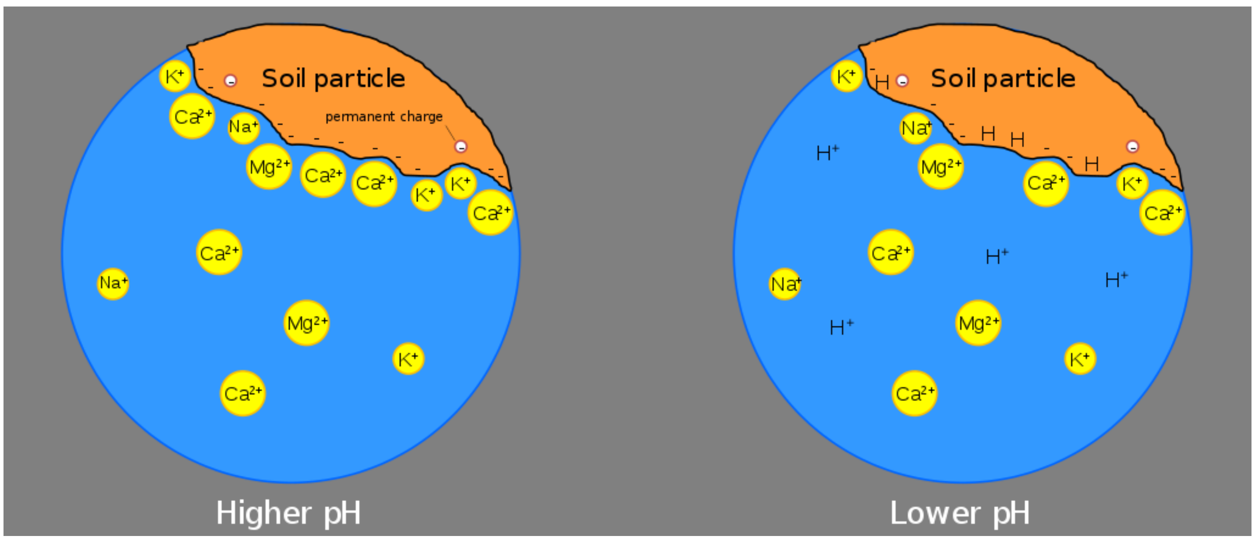

Figure 3. Soil cation exchange capacity (CEC) describes the ability of soil particles to retain positively charged ions. Soil CEC is greater at higher (more basic/alkaline) pH values, and inversely related to anion exchange capacity. Image source: Wikimedia Commons.

The anions, or negatively charged ions in Table 1, move more freely throughout soils as they attach to water molecules that move in various directions in the soil profile. They can be lost - or move away from the desired location via leaching - more easily than cations that are held by the negatively charged soil particles. There are nutrients in the soil that act as anion exchange sites as well; these sites with anion exchange capacity include aluminum and iron oxides and highly weathered soils. These sites hold onto phosphate, sulfate, nitrate, and chlorine. In most soils, the cation exchange capacity is greater than the anion exchange capacity. Anion exchange capacity is dependent on the pH of the soil and increases as the pH of the soil decreases.

Regarding pH, the hydrogen ion (H^+) plays a very important role in the soil. The concentration of the H^+ ion in the soil is known as pH and determines how "acidic" or "basic/alkaline" a soil is. This positively charged ion is good at attaching to negatively charged ions (opposites attract). If there are lots of hydrogen ions, such as a pH above 7.0 (basic/alkaline), they can claim bonding sites on negatively charged particles and make it difficult for other positively charged ions like potassium, manganese, and others to be held by the soils to be used by plants. If there are fewer hydrogen ions such as a pH below 6.0 (acidic), there can be deficiencies of calcium, magnesium, and molybdenum, and reduced bacterial growth which leads to reduced nitrogen availability. Soils can become acidic because hydrogen is added to soils by decomposition of plant residues and organic matter, or because hydrogen is a byproduct that results from nitrification of ammonium from additions of fertilizers, manures, or plant residues.

To control pH, or hydrogen ion concentrations, humans often apply “lime” as an amendment. Lime comes in a number of forms: calcium or magnesium (1) carbonates (calcium or magnesium atoms attached to carbon atoms), (2) oxides (calcium or magnesium attached to oxygen atoms), and (3) hydroxides (calcium and magnesium attached to hydrogen and oxygen atoms). Calcium and magnesium can neutralize or attach to the hydrogen ion. When added to the soil, the lime dissolves in water and releases a base molecule (OH^-, hydroxyl) into the soil. The base molecule reacts with the hydrogen ion in the soil to form water which decreases acidity and thus makes the soil more alkaline or basic. Lime can also be effective when the molecules remove H+ and Al^+ off of cation exchange sites.

Callout Note

The form of carbon shown in Table 1 is not an ion, it is instead a gas that is used during photosynthesis and is taken in by the plant through tiny holes in their leaves and stems, not through their roots. During photosynthesis, the plants utilize many of the nutrients taken up from the soil during the intermediate steps involved in converting carbon dioxide gas, water, and sunlight, into oxygen gas and sugars. Dioxygen gas, the plant available form of oxygen, is used for respiration, the opposite of photosynthesis in plants.

Physical and Biological Soil Health

It is important that nutrients, in plant available forms, are close to plant roots in soil or can move around in the soil structure, otherwise the plants cannot access them and use them to grow. Because of this, it is critical that nutrient management planning goes beyond just managing nutrients by adding amendments of plant available forms of nutrients by also addressing the physical and biological characteristics of the soil.

Structurally, it is important that soils are made up of a variety of sizes of soil aggregates - or clusters of soil particles (sand, silt, and clay), organic matter (carbon-based materials such as decomposed plant matter and animal compounds), air, and water. These clusters can be held together by sticky exudates from plant roots, fungal hyphae, and excretions from bacteria, worms, and other living things. These aggregates create a structure where biology can thrive. In a well-structured soil, plant roots and fungal hyphae can spread out, microbes can move about, water can infiltrate and flow in all directions or be stored, and air can circulate to bring nitrogen and oxygen gas molecules to microbes and plants.

It is important for soils to maintain these aggregates throughout the soil profile, including the very topmost layer. If the topmost layer is compacted or compressed from vehicle or animal foot traffic, wind or water moving loose soil particles to fill in empty air pockets, or soils broken up and crumbled by extensive tilling, then water and air cannot infiltrate the surface of the soil. This compaction and clogging can lead to drought-like conditions in the soils and flood-like runoff conditions overland and downstream when it rains. It can also lead to nutrient deficiencies in plants.

Within the soil profile, many plants extend their pool of resources by forming symbiotic relationships with mycorrhizal fungi which connect back to the plant roots (Fig. 4). Mycorrhizae can increase the surface area of nutrients plants have access to. The fungal filaments absorb, transport, and share nutrients with the plant. Some plants that form relationships with mycorrhizae include alfalfa, asparagus, basil, corn, cucumbers, fescue, garlic, onion, peas, peppers, potatoes, soybeans, Sudan grass, sunflowers, wheat and many more.

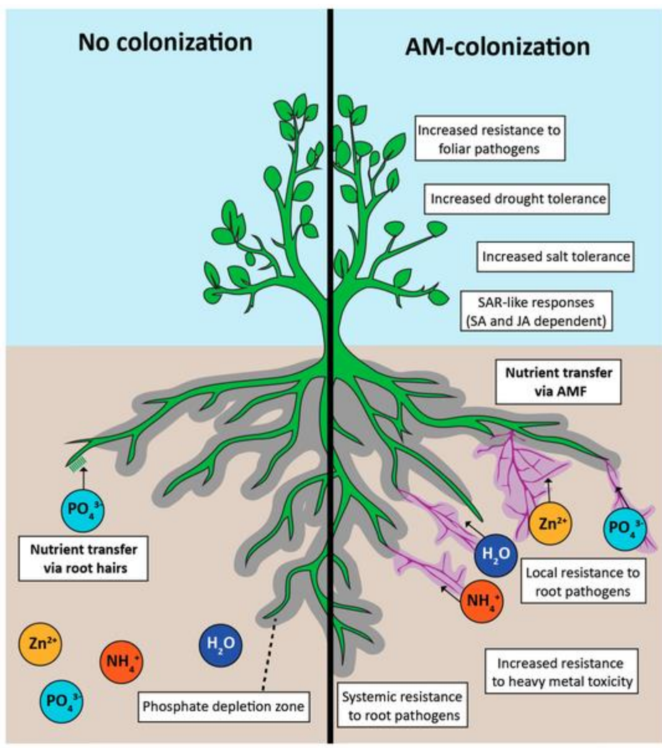

Figure 4. By forming symbioses with arbuscular mycorrhizal fungi (AM, the most common type of mycorrhizae), plants can access a greater volume of soil for nutrient and water uptake. Mycorrhizal symbioses may also contribute to crop tolerance of drought, salt, pathogens, and other stressors. Image source: Catherine N. Jacott, Jeremy D. Murray and Christopher J. Ridout, CC BY-SA 4.0 via Wikimedia Commons.

In addition to mycorrhizae, soil bacteria also support soil health. Soil bacteria can digest organic matter in soil to unlock nutrients into plant-available forms. Beneficial bacteria can suppress soil pathogens, keeping plants disease-free. Soil bacteria help build soil structure by contributing to organic matter formation and excreting glue-like substances that help hold soil aggregates together. These bacteria and other microbes that live in the soil need food, water, and shelter, just like larger livestock. By keeping the soil alive through limited disturbance, keeping the soil covered, and supporting a diverse variety of growing plants that feed microbes, the soil life will in turn continue to support the desired plants that land stewards are looking to produce. Using soil health principles to determine which practices are best suited for a particular landscape and production goal are key to successful nutrient cycling and management.

Nutrient Management is Complicated and has Consequences

In an ideal world, soils would be well-structured with thriving soil life and the exact amount of each nutrient would be applied at the perfect time for each individual plant's particular stage of growth. In the real world, this is simply not possible because of large scientific unknowns around precise plant nutrient needs, and, in practice, balancing labor, economics, weather, and the constantly changing environment and soil ecosystems.

Considerations such as plant growth stage, equipment availability, amendment nutrient ratios, climate, labor, and timing can all affect the impact of nutrients on plants and on the larger landscape. In some cases of amendment overapplication, too much of a nutrient can cause plants and microbes to become "lazy" and stop undertaking processes to transform or access nutrients on their own. Critically, overapplication can also cause salts to build up in soils, which can interfere with plant water, and therefore also nutrient, uptake, leading to drought stress even in well-watered soils.

When too much fertilizer is applied, it can leave the field where it was applied and harm the surrounding environment. This can happen in a few different ways. Some fertilizers, such as ammonium nitrate, contain highly soluble forms of nutrients, which can be easily lost through leaching and runoff. In other cases, fertilizers are not actually supplying ready-to-use plant available forms of nutrients. For example, nitrogen is often applied as ammonia fertilizer (NH_3), which is not one of the plant available forms in Table 1. Before it can be used by plants, ammonia must first dissolve in water. If too much ammonia fertilizer is used, not all of it can be dissolved, and it can leave the landscape in runoff and then build up in waterways, where it is toxic to aquatic life. Finally, other nutrients — most notably phosphorus — can

Callout Note

Soil amendments can provide more than just nutrients! In addition to containing essential nutrients like nitrogen, phosphorus, and potassium, organic amendments like manure and compost also add organic matter back to the soil. Soil organic matter improves water infiltration, water-holding capacity, and aeration by contributing to healthy soil structure. Plus, organic amendments tend to release nutrients more slowly than synthetic fertilizers, as the nutrients must be freed by soil microbes before they can be used by plants. This can reduce the amount of applied nutrients entering local waterways through leaching or runoff. Finally, fertilizing with manure from local sources helps "close the loop" – returning the nutrients consumed by animals from the landscape back into the soil as animal waste.

bind tightly to soil particles after application and become difficult for plants to access. Applying phosphorus fertilizer in appropriate amounts, and at times and locations where crops can take up the added phosphorus, is critical to prevent the buildup of excess (but plant-unavailable) soil phosphorus, which can then enter local waterways through soil erosion.

It is in the best interest of everyone to apply nutrients with as much accuracy as possible. If applied improperly, not only do plants lose out on critical nutrients, but land stewards can lose money and resources, and entire watersheds can be impacted by the negative effects of those nutrients entering waterways.

If nutrients accumulate in waterways and waterbodies, as opposed to in soils where land-based plants are growing and cycling those nutrients, water quality issues can arise. In particular, too much phosphorus in waterways has proven to be an issue in the Lake Champlain watershed (Fig. 5). Phosphorus is used by algae and microphytes that live in the water to build their bodies and reproduce, but these organisms only need about 0.02 to 0.03 mg/L of phosphorus to do this, whereas crops and land-based plants typically need about 0.2 to 0.3 mg/L of phosphorus to grow - that's a 10-fold difference in phosphorus concentration. When algae "blooms" because there is so much phosphorus to help it grow, it can produce huge populations that can take over large sections of a waterbody. The algae itself, if ingested, can cause flu-like symptoms in humans and death in pets. When algae dies, it is broken down by bacteria in a process that uses oxygen, reducing the oxygen available to fish and other aquatic life. This can lead to large dead zones where fish cannot survive. Too much phosphorus in waterways and waterbodies can therefore be harmful to all sorts of life which in turn hurts both ecosystems and economics.

Figure 5. Algae bloom in Lake Champlain near Swanton, VT. Image source: Glenn Russell via Burlington Free Press.

How to Manage Nutrients to Reduce Impacts to Water Quality
As discussed earlier, adding nutrients to the landscape is necessary for continued plant growth that leads to healthy ecosystems and human populations. But issues can arise when those nutrients are applied in the wrong quantities, forms, place, or time. To minimize the negative impact that nutrients might have on water, management strategies (a.k.a. practices) are designed for each land steward to maximize their goals while protecting the environment.

These practices have been fine-tuned to various soil types, field slopes, climate conditions, plant types, and other characteristics over time by scientists, technical service providers, and land stewards themselves. These practices are based on the goals of making nutrients available to plants in the right forms, right amounts, right place, at the right times (also known as the 4Rs of nutrient stewardship), while reducing the potential for nutrients to be lost or accumulate in locations that can cause negative effects (Fig. 6).

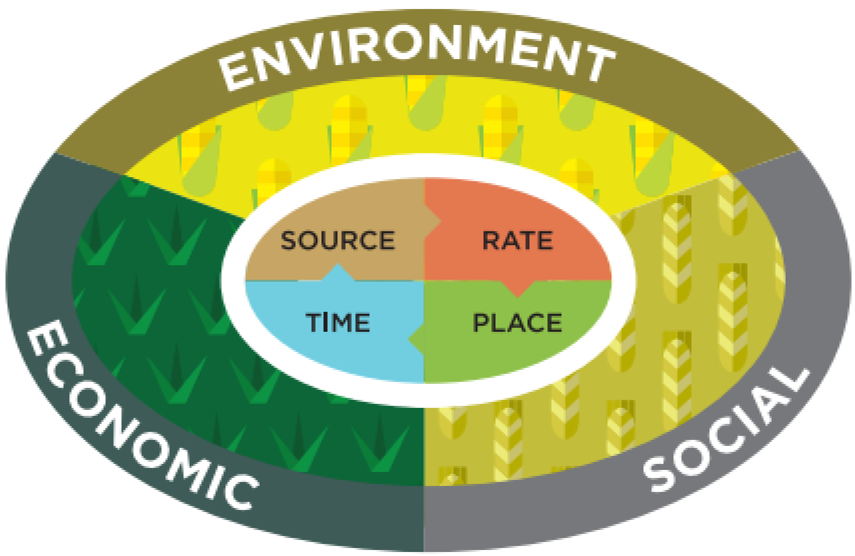

Figure 6. The "4 Rs" of nutrient management: right source, right rate, right place, right time. Managing nutrients with these principles in mind supports environmental, economic, and social good on working landscapes. Image source: 4R Pocket Guide from NutrientStewardship.org.

Some of these practices occur at the farmstead:

- Improve manure and/or feed storage areas with rain and leachate collection systems so that rainfall does not reach areas where nutrient-rich materials such as manure, fertilizer, or feed are being stored or stockpiled
- Improve trails and roads that aim to reduce compaction of soils so that water can infiltrate and not become concentrated

Others occur in the field:

- Plant vegetation in seasons and locations where the primary crop is not growing to reduce soil erosion and improve nutrient cycling and microbe populations- e.g., cover cropping, nurse cropping
- Implement no-till, reduced tillage, or conservation tillage which is designed to reduce erosion of soil with no or minimal disturbance which can improve the structure of soil, allowing for water to infiltrate and reduce runoff
- Leave residue to keep soil covered with plant material which can improve infiltration of water into the soil and reduce volume and speed of water moving across landscapes taking nutrients with it
- Practice rotational planned grazing to maintain healthy, vibrant, vegetation-filled paddocks that can better absorb and process nutrients
- Inject manure to reduce nutrient runoff and/or volatilization into the air. Conserving nutrients allows more for the crops to access and reduces fertilizer application
- Install grass waterways which are patches of perennial vegetation that help curb erosion in the field. They are designed to absorb energy from moving water while holding soil from eroding in areas where water is prone to moving in concentrated flow across crop fields.

Others occur near waterways:

- Plant and maintain woody riparian buffers or filter strips to both physically stop and slow water moving over the land thereby providing time for water and dissolved nutrients to infiltrate. The plant roots to help hold soils along the waterway banks in place to prevent bank erosion into the waterway
- Install exclusion fencing and streambank crossings keep animals out of vulnerable waterways where they can cause bank erosion or deposit their nutrient-rich waste directly into the waterways.

Others involve protecting or restoring critical ecosystem areas:

- Restore wetlands - wetlands in many landscapes have been drained and reshaped for other purposes, but if restored, those areas could act as nutrient storage and processing systems for large watersheds. Watershed restoration and no-touch areas through easements can be employed to accomplish these goals.
- Protect river corridors - the areas along rivers and streams function as floodplains that can help slow down water and store nutrients that are transported by waterways so that they do not build up downstream. Rivers and streams need to have access to these floodplains and need to be able to both remove and add sediment to the banks of these areas as they change in shape over time.

There are countless more practices and approaches that are currently in use and are yet to be discovered that can be applied within the larger context of a farming operation or at scales such as a backyard, Town Green, or a private forest.

Practices for various other scales:

- Keep grass lawns at 4” high planted with a variety of species
- Reduce the use of bio-cides (pesticides, fungicides, etc.) that are designed to kill living things
- Incorporate more green spaces and rain gardens as opposed to pavement, where possible
- Use grassed waterways and ditches, turnouts, properly sized culverts, and other practices along roads to slow and spread stormwater runoff across land
- Size water treatment facilities appropriately for relevant volumes
- Follow the Accepted Management Practices for Forestry, such as utilizing advanced equipment that reduces compaction of the forest floor, or skidder bridges that reduce streambank erosion in forests
- Take a soil test for your garden or lawn before applying fertilizers. If applying amendments, do not apply more than recommended.

In all of these scenarios and landscapes, it is critical to understand the history of the place, how it has been stewarded in the past and by whom, and how to best steward it for all of the generations of humans and other species to come in the future. Humans can play an important role in supporting natural cycles and systems of nutrients, water, and energy by paying attention and learning from natural systems and observing in areas where restoration and regeneration are occurring.

Conclusion

Human-stewarded lands can be designed and managed in ways that are in sync with natural nutrient cycles. It is important for land stewards to understand the science of nutrient management and soil health to make informed decisions and interpret the variety of feedback that their landscapes are providing. Proper planning, practice implementation, and observation of natural systems can reduce issues related to nutrient management and water quality across all land stewardship scales. There are resources available to land stewards through existing institutions, courses, written and recorded lessons, word of mouth, and technical service providers who can help design and implement land stewardship plans that are context-specific to provide for healthy and thriving landscapes, waterways, and human economies.

Where to Learn More

Vermont Natural Resources Conservation Districts
University of Vermont - Extension
USDA – Natural Resources Conservation Service (NRCS)
Vermont Agency of Agriculture, Food, and Markets
Vermont Agency of Natural Resources
Vermont Housing and Conservation Board