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Nitrogen Cycling in Flooded Taro Agriculture

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Nitrogen (N) is an essential element in plant nutrition that is often a limiting factor in taro production systems. Efficient management of N is critical to ensure growers achieve target yields while simultaneously protecting valuable water resources. Insufficient N limits taro yields, whereas excess fertilizer N impairs water quality, with adverse effects on fragile fresh and marine water ecosystems. Nitrogen cycling in flooded agroecosystems is complex and difficult to predict. The purpose of this publication is to present an overview of the N cycle in a flooded environment, with a focus on the fate of plant-available N. This publication uses data gathered from field measurements and laboratory experiments conducted in Hawaiʻi to illustrate specific pathways within the N cycle in flooded taro. With a better understanding of this complex system, farmers and agricultural professionals will be better placed to improve N fertilizer use.

The Flooded Taro Environment

The flooded taro environment consists of four distinct but interconnected zones: (1) the air above the ponded water, (2) the overlying surface water, (3) the thin aerobic surface soil layer, and (4) the anaerobic subsoil layer (Fig. 2). The diagram shows that N is subject to a number of different transformations depending on its form and location within the different zones. Some of the transformations represent potential gains in plant-available N (mineralization and biological nitrogen fixation, or BNF), while others are losses (denitrification and volatilization). The transformations depend on a number of environmental factors including oxygen status, pH, temperature, amount of organic matter, and microbial population.

Figure 1. Loʻi kalo production in the fertile soils of Hanalei Valley on the Island of Kauaʻi.

Nitrogen Forms and the N Cycle

Nitrogen in a taro system exists as inorganic dissolved ions (ammonium, or NH_4^+, and nitrate, or NO_3^-), more complex organic molecules associated with soil organic matter, and gaseous N. Taro roots take up dissolved

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inorganic N primarily as NH_4^+, which is the dominant ionic form, and to a lesser extent NO_3^-. The largest pool of N in the soil occurs as organic N in the form of amino acids, amines, proteins, and larger humic compounds. In large part, these compounds are not directly available for uptake by taro roots and must be converted into inorganic forms before they can be used by plants. Nitrogen can also exist in gaseous forms as a component of ammonia (NH_3), di-nitrogen (N_2), and nitrous oxide (N_2O).

The form of N at any given time depends on a number of soil chemical and biochemical processes that collectively represent the N cycle (Fig. 2). Primary N inputs (gains) into the taro system include the following: 1) organic and conventional fertilizers; 2) incorporation of crop residues, green manure residues, and organic matter; 3) BNF; and 4) N in irrigation water. Potential N losses from the system include the following: 1) N removed by the crop via root uptake; 2) N losses through water outflow from the field or leaching into the groundwater; and 3) losses through various chemical and biochemical transformations, including denitrification and volatilization.

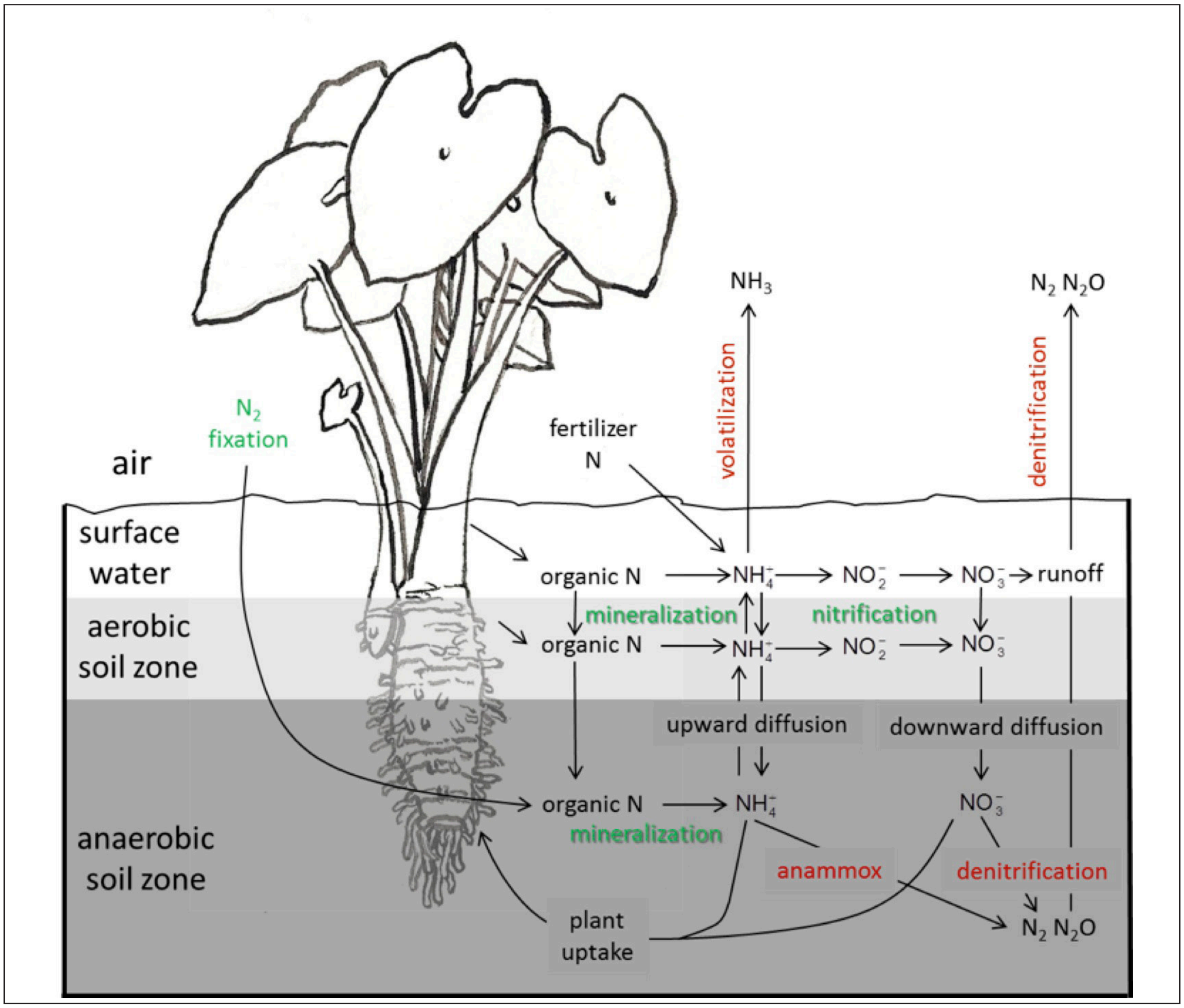

Figure 2. Processes controlling the transformations of N in the surface water and aerobic and anaerobic soil layers in a flooded taro system. Red text represents losses of plant-available N, and green text represents additions of plant-available N (drawing adapted from Mitsch and Gosslink (2007) and Reddy (1982) (taro art by Solomon Enos).

Role of Oxygen

The oxygen (O_2) status of the water and sediment layers plays a key role in determining potential N-transformation pathways. In the presence of O_2 (aerobic conditions), oxidizing reactions predominate, resulting in the conversion of NH_4^+ to NO_3^-. In the absence of O_2 (anaerobic conditions), reducing conditions prevail, promoting the gaseous loss of N (i.e., NO_3^- to N_2O). Typically, the overlying water is aerobic because it is in equilibrium with atmospheric O_2. *In situ* O_2 measurements performed at four different taro farms on Kaua‘i, O‘ahu, and Hawai‘i Islands showed that O_2 concentration in the overlying water ranged from 1.99 to 8.57 mg L^{-1} with a mean value of 5.74 mg L^{-1}. Aquatic life becomes stressed when dissolved O_2 concentrations drop below 5 mg L^{-1}. The soil layer consists of two zones: an aerobic layer at the soil–water interface where O_2 is replenished from the overlying water column, producing oxidizing conditions, and an underlying anaerobic zone characterized by reducing conditions. The aerobic layer is generally thin (<1 cm), but its relative thickness can show considerable variability across sites. Figure 3 shows an example of how the O_2 status in taro fields can vary. In the first example (Lo‘i 1), O_2 penetrates into the surface soil layer, maintaining aerobic conditions to a depth of 3 mm. On the other hand, Lo‘i 2 shows a situation where anaerobic conditions begin within a millimeter above the soil surface and persist throughout the soil layer. The presence of high levels of organic matter tends to reduce dissolved O_2 concentrations because the high organic matter stimulates microbial activity and O_2 consumption.

Nitrogen Transformations in Soils

N-mineralization: Nitrogen in soil exists primarily as organic N in the soil organic matter. Organic N is readily converted into inorganic N (NH_4^+ and NO_3^-) by microorganisms as they break down organic matter to get energy. The conversion process, termed N mineralization, represents an important source of plant-available N. Nitrogen mineralization occurs under both aerobic and anaerobic conditions, although it proceeds more rapidly in the presence of O_2. In the absence of O_2, the mineralization process only produces NH_4^+, which is available for plant use. The capacity of a soil to mineralize N is called N-mineralization potential. The amount of organic matter in the soil and how the soil is managed are two critical factors determining a soil's N-mineralization potential. Taro soils under organic management tend to have higher concentrations of total N and exhibit higher N-mineralization potentials compared to soils under conventional management. The graph in Figure 4 depicts the N-mineralization potential of a taro soil under conventional fertilizer management (red) and another under organic management (green). The soil that had received organic fertilizers for more than 10 years shows a much higher potential to mineralize N than the conventionally managed soil. These data highlight the

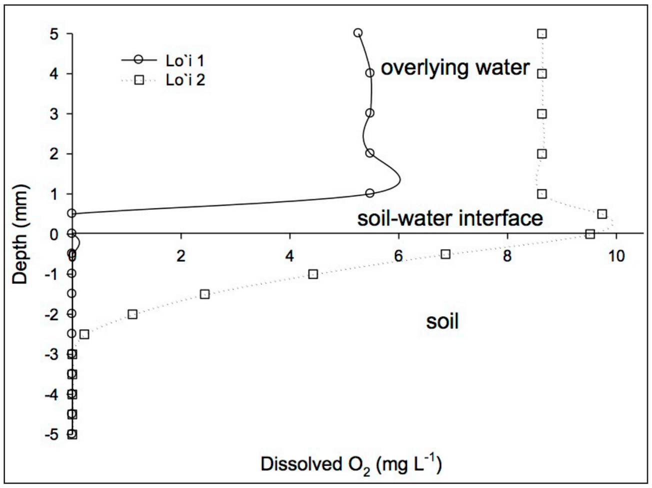

Figure 3. Range of measured dissolved O_2 in the floodwaters and sediment of cultivated lo‘i.

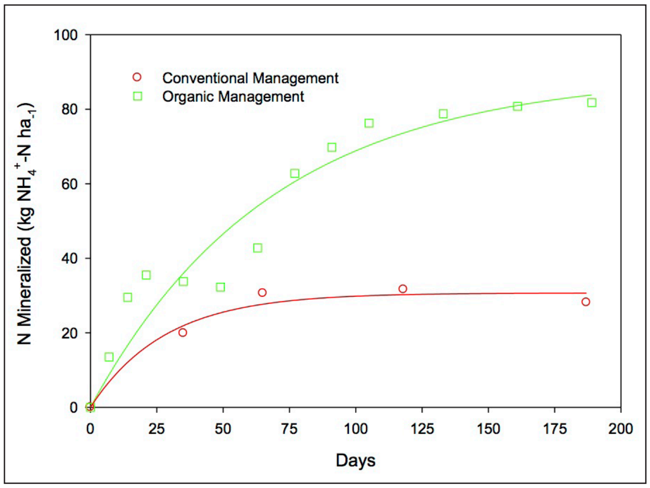

Figure 4. Nitrogen-mineralization potentials of two Hanalei series lo‘i soils as affected by type of soil management.

important role organic inputs play in maintaining a soil's ability to supply NH_4^+. Enhancing soil organic matter increases N-mineralization potential and can reduce N inputs from fertilizer.

Nitrification: Nitrification is the biochemical conversion of NH_4^+ to produce NO_2 and then NO_3^- mediated by the soil bacteria *Nitrosomonas* and *Nitrobacter*. The reaction can only occur in the presence of O_2 and proceeds in two steps, as follows:

$$NH_4^+ + 1½O_2 \xrightarrow{Nitrosomonas} NO_2^- + 2H^+ + H_2O + 275kJ\ energy \qquad \text{EQN 1}$$

$$NO_2^- + ½O_2 \xrightarrow{Nitrobacter} NO_3^- + 76kJ\ energy \qquad \text{EQN 2}$$

Ammonium in the aerobic surface water and surface sediment is readily converted to NO_3^- through nitrification. Nitrification can also occur in the oxidized rhizosphere of taro grown in flooded soils (Figure 2). Similar to other wetland plants, taro transports atmospheric O_2 through its stem down into the subsoil, where the O_2 diffuses out of the roots into the soil, creating a thin aerobic region adjacent to the root. In aerobic environments the NO_3^- can accumulate and serve as a pool of plant-available N. However, at aerobic and anaerobic interfaces such as those commonly found in a flooded taro environment, the NO_3^- has a tendency to diffuse into anaerobic layers where it is rapidly lost through denitrification.

Denitrification: Denitrification is a stepwise series of reduction reactions carried out by a diverse group of anaerobic bacteria that converts plant-available NO_3^- into gaseous N (N_2O or N_2) that eventually escapes from the soil and enters the atmosphere. Nitrous oxide is an important greenhouse gas with 300 times the heat-trapping capacity of CO_2. In the absence of O_2, denitrifying bacteria readily use NO_3^- as the terminal electron acceptor as they obtain energy from organic matter. The reaction is as follows:

$$2NO_3^- \xrightarrow{-2[O]} NO_2^- \xrightarrow{-2[O]} 2NO\uparrow \xrightarrow{-[O]} N_2O\uparrow \xrightarrow{-[O]} N_2\uparrow \qquad \text{EQN 3}$$

The denitrification reaction occurs at the aerobic–anaerobic interface where NO_3^- produced from nitrification in aerobic soil regions (surface sediments and the rhizosphere) diffuses into adjacent anaerobic zones where it is rapidly denitrified. Recent sampling across a range of taro fields in Hanalei and Waiāhole found that nitrifying and denitrifying bacteria are present in large numbers and active. Comparisons between conventionally and organically managed taro fields indicate that taro fields receiving conventional fertilizers show a much higher denitrification potential than taro fields under organic management.

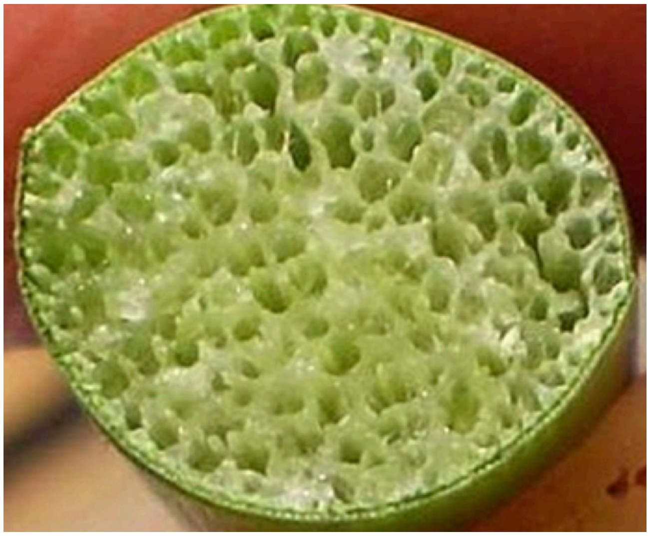

Figure 5. The stem of an aquatic plant showing presence of hollow arenchyma that act as conuits of atmospheric O_2 into the rhizosphere.

Rhizosphere nitrification and denitrification: As discussed earlier, taro sediments are mostly anaerobic, except for a thin aerobic surface layer and aerobic soil regions adjacent to taro roots. Taro stems, like the stems of other wetland plants, contain hollow channels (arenchyma) that act as conduits transporting air from the atmosphere down to the root-zone (Fig. 5). Oxygen transported through the plant ends up in the root tissue, where some of it diffuses out into the adjacent sediment, producing a thin zone of aerobic soil, surrounded by the anaerobic bulk soil. Using an O_2 microelectrode, we have demonstrated that the aerobic zone can extend as much as 2 mm from the taro root. In a whole-core taro experiment, we measured significant losses of plant-available NH_4^+ through the coupling of nitrification and denitrification in the rhizosphere of taro plants (Penton et al. 2013) (Fig. 6). In the aerobic rhizosphere, nitrifying bacteria readily convert NH_4^+ to NO_3^-, which is either taken up by taro roots or diffuses into the adjacent anaerobic zone. Once in the anaerobic zone, NO_3^- is rapidly lost through denitrification. Through careful experiments we have found that as much as 35% of NH_4^+ in the subsoil can be lost through the coupling of nitrification and denitrification in the rhizosphere. Other experiments have shown that nitrification/denitrification reactions in the rhizosphere of flooded rice plants are also a significant pathway for the loss of plant-available NH_4^+.

Ammonia volatilization: Ammonium dissolved in the water can be converted into NH_3 gas through a process called ammonia volatilization, representing a loss of plant-available N. The conversion process is controlled by the pH of the overlying water. At pH 7.0 or less, for example, NH_4^+ is stable in water, and it is not subject to volatilization. As pH rises, however, NH_4^+ converts to NH_3 and is lost to the atmosphere. The volatilization reaction increases sharply when pH rises above 8.5, with as much as 35% loss at pH 9. The pH of the overlying water column in flooded taro fields can vary widely from acidic (<6) to alkaline (>9) conditions between the morning and afternoon. This large daily fluctuation of pH is due primarily to algal growth and consumption of CO_2 during photosynthesis. During the morning hours when photosynthesis is low due to lack of sunlight, dissolved CO_2 keeps the water acidic. As the day progresses, algal photosynthesis rates increase, reducing dissolved CO_2 concentrations and thus causing a steady rise in water pH. Sampling several taro fields in Hanalei Valley confirmed a rise in water pH between morning and afternoon. Samples collected between 8 and 10 AM showed a mean pH of 6.2, while samples collected at the same locations between 1 and 3 PM showed a distinct rise to 8.0, with maximum pH values measured at 9.1 (Fig. 7). Overall, the data indicate that afternoon increases in the floodwater pH in young taro fields produce conditions that are more favorable for the loss of plant-available NH_4^+ through volatilization. On the other hand, in mature taro fields, where the leaf canopy shades the water throughout the day, water pH remains below 7 consistently.

Anammox: Anaerobic ammonium oxidation (anammox) involves the anaerobic oxidation of NH_4^+ coupled with NO_2 reduction to create N_2 gas. The reaction is mediated by a group of autotrophic bacteria that inhabit anoxic sediment layers. The presence of NH_4^+ and NO_3^- in the oxic surface layer, coupled with NO_3^- reduction to NO_2 in adjacent anoxic layers, is a prerequisite condition that provides a consistent supply of NO_2 for anammox bacteria. Anammox was first documented in wastewater treatment facilities in the Netherlands in the early 1990s, and it has since been found in a broad range of environments, including river sediments, wetlands, and paddy rice fields in Asia. A survey of flooded taro

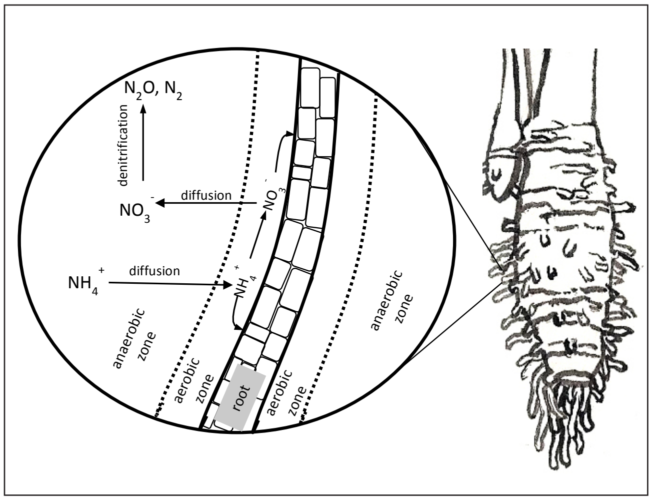

Figure 6. The presence of an aerobic zone surrounding taro roots allows for the coupling of nitrification and denitrification in the subsoil of flooded taro fields.

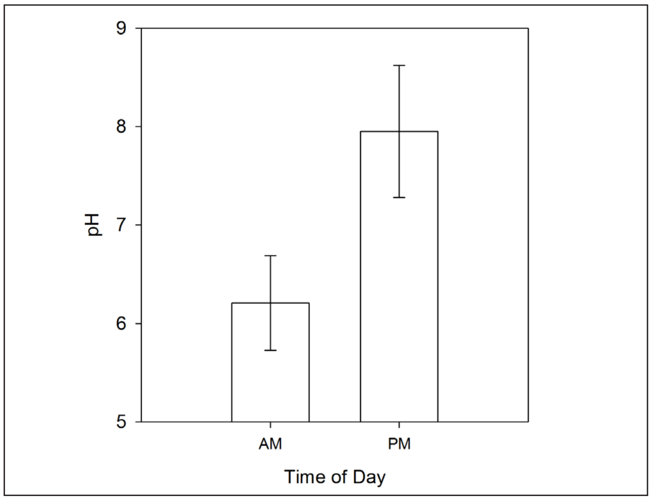

Figure 7. Time of day effects on water pH in taro fields of Hanalei Valley.

sediments from Oʻahu (Waiāhole and Haleʻiwa) and Kauaʻi (Hanalei) confirmed the presence of anammox bacteria, but incubation experiments using the isotope-pairing technique revealed that the anammox reaction was not contributing significantly to NH_4^+ loss. Similarly, anammox activity in paddy rice fields in Japan and China showed the presence of anammox bacteria, but isotope-pairing experiments showed negligible contributions to N loss. These results suggest that anammox is not a contributor to N loss in managed flooded agroecosystems.

Nitrogen Management

Nitrogen inputs play an important role in the production of wetland taro. Efficient management of N fertilizers must consider the source of N, its application rate, the timing of application, and its placement in the field.

Nitrogen Source: Taro plants preferentially use the NH_4^+ form of N, and therefore fertilizer materials that release NH_4^+ are preferred over fertilizers composed of NO_3^-. There are many types of N fertilizers available to taro growers, including soluble synthetic products and many organic amendments. Synthetic products such as urea (46-0-0) and blended fertilizers (16-16-16, 10-10-10, etc.) are commonly used in conventional taro fields because they contain soluble urea that readily hydrolyzes to NH_4^+ when added to the flooded soil. Ammonium sulfate (21-0-0) is another synthetic fertilizer commonly used in taro production. Urea-based fertilizers and ammonium sulfate provide a rapidly available source of NH_4^+ that is easily used by taro roots. Nitrate-containing fertilizers such as $CaNO_3$ (15.5-0-0, 19% Ca) and KNO_3 (13-0-46), while well-suited for dryland crops, are not effective in flooded soils because the NO_3^- form of N is quickly denitrified to N_2 gas when it moves into the anaerobic sediments common in flooded taro fields. Applying NO_3^--based fertilizers is not recommended for wetland taro production. Organic fertilizers such as feather meal, blood meal, fish meal, and chicken manure are good sources of NH_4^+. Organic forms of N in animal-based waste materials are readily mineralized into NH_4^+ under both flooded and dryland conditions. Nitrogen-rich materials (feather meal, blood meal, fish meal) are relatively rapid sources of NH_4^+, whereas steer manure, green waste, and low-N compost materials supply less N more gradually over time. Organic materials tend to release N into NH_4^+ form at a slower rate than soluble synthetic fertilizers, thus reducing potential for losses. In addition, organic materials are much more than just suppliers of N. They are typically good sources of P, Ca, S, and the micronutrients, and they provide added benefits to the physical, chemical, and biological properties of soil.

Timing and Placement: Currently, most commercial taro farms apply a small portion of N as a pre-plant application prior to flooding, with the remaining N broadcast as urea or ammonium sulfate granules into the flooded taro fields at monthly intervals through the first six months of production. The fertilizer pellets sink and come to rest in the aerobic zone on the sediment surface where they dissolve rapidly, releasing NH_4^+ which is then subject to a number of potential loss pathways (Fig. 8). If the floodwater pH is high (>8), NH_4^+ is readily volatilized to NH_3 gas and lost to the atmosphere. In the presence of O_2, NH_4^+ is rapidly converted into NO_3^- by soil bacteria (nitrification) and subsequently lost through denitrification as the NO_3^- diffuses into the anaerobic subsoil. Thirdly, dissolved NH_4^+ and NO_3^- in the surface sediment readily diffuse into the floodwaters and can exit the taro field and pose a downstream contamination threat. For all of these reasons, it is recommended that N fertilizers be applied to the subsoil of flooded taro fields. Placing the fertilizer in the subsoil is preferable for the following reasons: 1) N is conserved in the NH_4^+ form; 2) nitrification is minimized, reducing the potential for denitrification; 3) subsoil pH tends to be below 7, preventing N loss through ammonia volatilization; and 4) reactive forms of N, primarily NH_4^+, is kept separate from overlying waters, reducing potential for downstream contamination. Controlled-release conventional fertilizers or organic amendments release NH_4^+ more slowly than urea, and thus can be added as a one time amendment to the subsoil prior to planting and supply adequate N to taro during the first six months of the crop. In addition to the environmental benefits, a one-time pre-plant fertilizer application offers an opportunity to reduce labor costs associated with monthly urea applications.

Summary

Nitrogen is subject to a number of transformation pathways in flooded soils, some of which increase its availability for plant use (i.e., mineralization and nitrification) while others decrease availability (ammonia volatilization and denitrification). Taro plants preferentially use NH_4^+ in flooded soils, but NH_4^+ is subject to three primary loss pathways – ammonia volatilization, coupling of nitrification and denitrification, and loss in outflow water. Placing fertilizers, both conventional and organic forms, in the subsoil conserves N in the preferred NH_4^+ form, reducing losses to volatilization and denitrification and minimizing N contamination of downstream environments. Controlled-release forms of synthetic fertilizers and organic amendments applied to the subsoil one time prior to planting provide the following potential benefits: slow release of NH_4^+ to the soil in synchrony with taro N requirements; protection of N in the NH_4^+ form in the subsoil, reducing potential losses; and a reduction in labor time associated with monthly applications of urea.

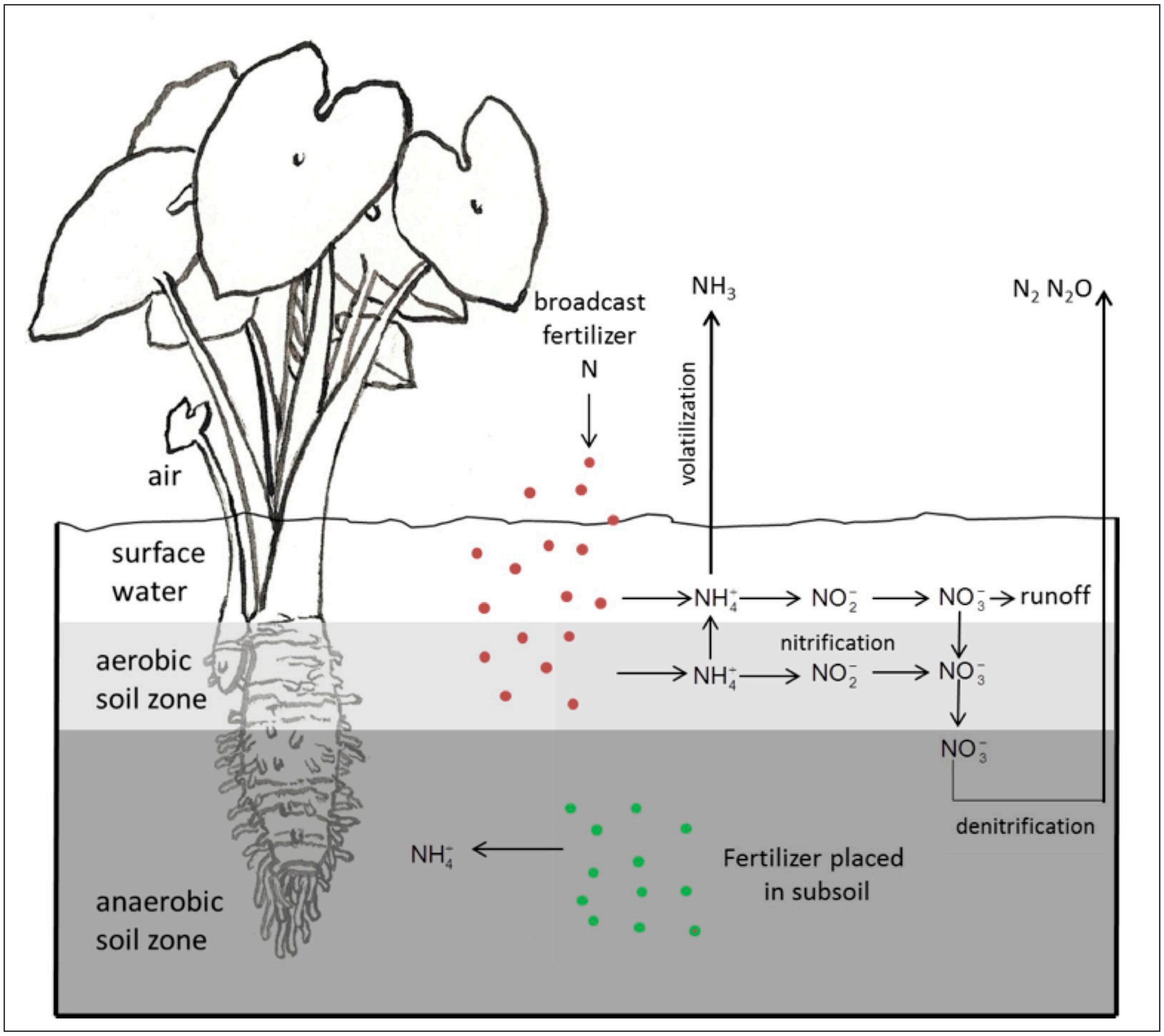

Figure 8. Nitrogen fertilizers (red dots), synthetic or organic, placed in aerobic zones (surface water and aerobic soil surface layers) are subject to reactions (nitrification + denitrification and volatilization) that increase likelihood of loss. Fertilizers placed in the anaerobic subsoil (green dots) are exposed to fewer potential loss pathways.

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