CHAPTER THREE

Soil and Nutrient Management

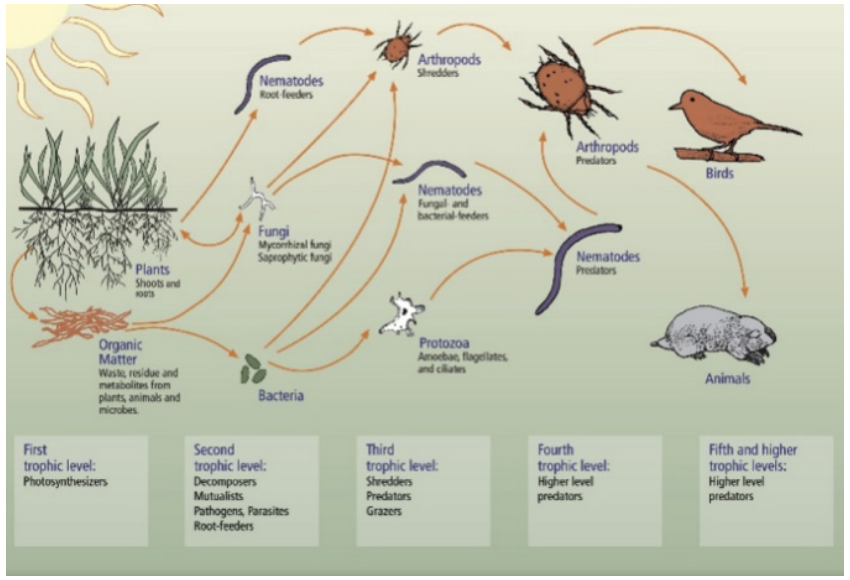
Soil Management for Crop Productivity and Quality

Maximizing soil health and fertility is critical to the success of any dairy farm. Best management practices such as good grazing systems, forage diversity, soil testing, liming, and adding fertility amendments can keep the soil healthy and forages productive and nutritious. It is important to remember that soils are complex systems composed of **physical, chemical, and biological properties**. Understanding each property and how it impacts soil function is critical in making management decisions that support crop productivity and quality.

Physical attributes of soils include texture, structure and drainage, depth, and erodibility. Soils are composed of various-sized particles of sand, silt, and clay. Sand is coarse, while clay is fine. Texture is defined by the proportions of these particles in the soil. Particles also stick together to form larger aggregates. Different-sized particles and aggregates don't fit together perfectly, leaving spaces between them through which air and water can infiltrate (Figure 8). The structure allows soil to hold and drain water, provides space for plant roots to grow, and creates a hospitable environment for soil microbes and other fauna to live.

Figure 8. Soil structure in various conditioned soil.

Source: Susan Brouillette



It may not seem like there is much life in soil, but in fact it is teeming with all kinds of life!

Farmers must address multiple aspects of each of these three properties to provide the best environment for crop production.

Figure 9. Soil biological diversity.

Source: Tugel, Lewandowski, & Happe-vonArb. 2000

The **chemical** properties of soil include the nutrients, pH, and ability for the soil to retain nutrients. These properties can be measured through traditional soil analyses and are typically involved in managing crop fertility on farms.

It may not seem like there is much life in soil, but in fact it is teeming with all kinds of life! **Biological** components make up the biological properties of soils. Soils provide homes for a diverse array of life, including earthworms, arthropods, nematodes, fungi, bacteria, and small mammals (*Figure 9, above*).

A soil's ability to balance physical, chemical, and biological properties and support productive, high-quality crops is often referred to as **soil fertility**. Farmers must address multiple aspects of each of these three properties to provide the best environment for crop production. A healthy, fertile soil should exhibit characteristics described below.

- High soil organic matter content
- High biological activity
- Good soil tilth
- Minimal to no erosion
- Proper soil pH
- Balanced nutrients

High Soil Organic Matter Content

Organic matter is composed of living, actively decomposing, and fully decomposed materials. In grass-fed dairy systems, organic matter is typically added to the soil through decaying plants and soil biological life, and manure that is deposited during grazing or otherwise spread on fields throughout the season. Microorganisms break down this organic material and incorporate it into the soil profile, where it can remain for long periods of time. Organic matter serves several purposes. First, it helps retain nutrients; organic matter particles are negatively charged and therefore attract positively charged nutrients such as calcium, magnesium, potassium, ammonium, and sodium; this is referred to as the cation exchange capacity (CEC). Plants utilize this nutrient bank by replacing these bound nutrients with root exudates, thereby releasing them into the soil solution where they can be taken up by the plant roots. Second, organic matter helps hold water that can be accessed by plants and microorganisms as it is needed, especially in times of drought. Finally, organic matter provides habitat for the vast array of soil fauna that play a crucial role in the soil's function. Organic matter levels in perennial systems can be quite high because this material accumulates overtime and is much slower to break down. It is not uncommon to see perennial grass fields with organic matter contents above 6%, while fields that experience annual tillage may struggle to sustain 3% organic matter.

High Biological Activity

Healthy soils are very biologically active because creatures living in the soil are responsible for breaking down organic matter in to forms of nutrients that plants can utilize. For example, plants prefer to utilize nitrate (NO3) instead of ammonium (NH4) due to the extra energy required to remove hydrogen from the molecule. Ammonium can be converted to nitrite (NO2) and then nitrate through a two-step process called nitrification. Each step requires a very specialized type of nitrifying bacteria. Without sufficient populations of these bacteria, the nitrogen cycle, and ultimately plant productivity, will be compromised. Soil biological activity requires ensuring the environment is hospitable to soil microorganisms such as bacteria. Just like cows, soil microorganisms need food, air, water, and a comfortable place to live. These are provided by organic matter and access to air and water in soil pores. Therefore, soil biological activity is tightly connected to having adequate soil structure.

Good Soil Tilth

Organic matter and exudates from microorganisms help soil particles form aggregates. Between aggregates, pockets of air and water can be trapped and then utilized by microorganisms to cycle nutrients. This porous structure of soil is referred to as soil tilth. Although farmers have little influence over the texture of soil, tilth can be impacted by management. Tillage breaks compacted soil into smaller aggregates, reintroducing air and water. However, tilling wet soils can lead to compaction and poor condition. In grass-based systems in which tillage is less frequent, poor soil tilth is typically associated with compaction from haying or manure spreading equipment or from grazing animals. A general rule of thumb for identifying if soil can be tilled is to roll some soil into a ball and drop it onto the ground; if it breaks apart, the soil is dry enough to work up. Likewise, giving animals access to a pasture when the soil is too wet can be just as destructive to the soil structure as plowing it. Mechanical aeration may help alleviate compaction. Aerators are implements with blades, typically about six inches long, that penetrate into the soil and lift it slightly as they roll over the surface. This breaks up the compacted layer and introduces oxygen back into the soil, increasing water and air infiltration, stimulating microbial activity, and allowing roots to penetrate deeper into the soil profile. A keyline plow or subsoiler may also be used to aerate soils but can be more aggressive than an aerator. These implements are designed to provide aeration deep in the soil by lifting and breaking compacted layers. The metal shanks and boots come in designs that differ in the amount of soil disturbance they cause and the horsepower needed to pull them through the soil. Aeration typically alleviates compaction symptoms temporarily. Further compaction should be prevented through management and monitoring. Poor soil tilth may also be related to overgrazing damage, whereby plant roots which would otherwise help provide soil aeration and reduce compaction are diminished. Growing deep-rooted forages such as alfalfa or forage radish can penetrate compaction layers and create pore spaces to improve soil quality. Grazing management with pasture rest periods can also help prevent soil compaction and promote plant root growth.

Minimal-to-no erosion

Erosion is the act of soil being transported from one place to another by a natural force such as wind or water. Erosion is more likely to occur after soil is tilled or when soil is left bare because plant cover and root systems help to protect and stabilize the soil surface, reduce soil erosion and runoff, and increase water infiltration. When soil erodes, it takes nutrients bound to it. This can pose environmental concerns, as nutrients can be carried into a body of water where they can be detrimental. Furthermore, erosion can destabilize field slopes or banks, posing danger to animals walking over them.

> In grass-based systems, overgrazed pastures diminish the vegetative cover, leaving the soil vulnerable to erosion.

Proper pH

pH is a measure of the acidity of the soil solution. It is measured on a scale from 1 to 14.A pH of 7 is considered neutral, less than 7 is considered acidic, and greater than 7 is considered basic or alkaline. Most agricultural crops require a pH of between 6 to 7 for optimal growth because pH impacts soil nutrient availability. As shown in Figure 10, most essential nutrients are highly available within this pH range. Furthermore, many important nutrient cycling processes require soil microorganisms that thrive at similar pH levels. A soil test should be used to determine the pH, and most laboratories will provide recommendations for attaining the correct pH for the crop. Legumes prefer slightly higher pH levels than most other agricultural crops; the pH for legumes ideally should be 6.5–6.8. Of the acres surveyed in aforementioned studies, 75% were below this optimal pH for legumes. Furthermore, 46.0% of fields were below a pH of 6.0, which limits nutrient availability for any crop.

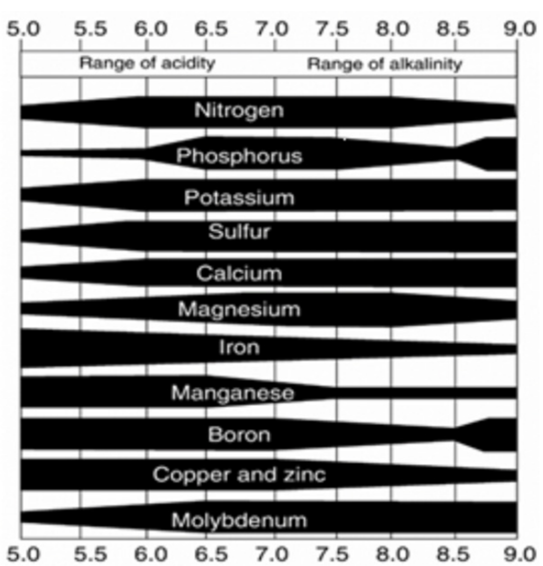


Figure 10. ph and nutrient availability.

Source: Little & McCutcheon, 2016

Balanced Nutrients

Plant nutrients are separated into two categories: macronutrients and micronutrients. Macronutrients are required by the plant in large quantities. These include nitrogen (N), phosphorus (P), and potassium (K). Micronutrients are required by the plant in small quantities. These include boron (B), calcium (Ca), chlorine (Cl), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn). Although required in small quantities, trace minerals are integral in many growth and maintenance functions for plants, just as micronutrients are important to livestock. Soil testing helps identify current

nutrient levels in soil. Soils deficient in any of these nutrients will translate into poor crop yields and quality. Therefore, correcting nutrient deficiencies, especially prior to seeding, is critical to maximizing crop productivity and quality. Fertility can be added through purchased fertilizers, importing manures, or growing leguminous crops. Farmers who rely on legumes to supply N should make sure soil pH and micronutrient levels, especially B, will support legume growth. Proper balance of macronutrients and micronutrients is dependent on previously mentioned factors like proper pH, appropriate soil structure, and good biological activity. Varied fertility amendments such as manure, composts, lime, rock dusts, and other mineral fertilizer sources can both help improve crop nutrition and support soil biology and physical properties. More information about soil testing and developing nutrient recommendations is found in the resource list at the end of this chapter.

Case Study: Soil Fertility on Organic Dairy Farms in Vermont

With a long history of dairy farming in the state, many Vermont farms observe excessive soil nutrient levels that if not properly managed can pose a threat to the environment. Through courses offered by Dr. Heather Darby at the University of Vermont Extension, farmers have learned basic soil, crop, and nutrient management strategies they can implement on their farm to grow high yielding crops while protecting surrounding natural resources. She has seen an increasing number of grass-based organic and other dairy farms participate in related courses. Instead of seeing excessive fertility levels, many farms have seen nutrient-deficient fields that require substantial fertility additions to meet crop demands. To investigate this finding, organic dairy farmers participating in these courses in 2015 shared their soil fertility data with UVM Extension. Of the 3,000 acres included, 78% and 91% had soil test levels below the optimal level for crop growth for phosphorus (P) and potassium (K), respectively. Less than 5% fell into the "excessive" category for either nutrient. Based on their nutrient application records, farms were not meeting the nitrogen (N) demand of the crop on 92% of their collective acreage. Several factors seem to be influencing this. It may not seem like it, but grass requires a lot of N. A stand of perennial cool-season grass (such as orchardgrass) producing 3–4 tons of dry matter per acre across the season requires **150 lbs. of N per acre**. Conversely, a mixed stand of grass and N-fixing legumes producing similar yields requires only 40 lbs. of N per acre. The majority, 57.9%, of the acres included stands with <20% legumes. With the increased land often needed to meet organic grazing standards, manure resources on organic farms are spread across more acres than on a comparably sized conventional farm. Therefore, meeting the N needs of an all-grass stand on an organic farm can be very challenging without importing additional nutrients.

75% of fields below optimal pH > 58% have <20% legume > 92% of fields not meeting crop N need

Grass-fed Dairy and Soil Management

While soil principles apply to grass-fed farms, farms that transition to grass-fed must consider additional specific factors. As previously mentioned, on grass-fed farms there is no grain, and nearly 100% of the diet must come from forages. To achieve the level of nutrition required to feed an all-forage diet to the herd, the soil must be able to provide adequate nutrition to forages.

Since cows only eat forage, the amount of forage required to feed the herd will increase. Likewise, the number of acres of land to be able to grow the increased amount of forage will also increase. Maintaining yields and quality on an expanded land base needs to be recognized as an investment and cost to transitioning to grass-fed dairy. To minimize the number of acres required, farmers should prioritize maximizing yields and digestible fiber per acre.

Generally, most organic farms fertilize with their own manure. Some farms also import additional nutrients to maintain fertility. If transitioning to grass-fed production, it is likely that the amount of manure and the quality of the manure will change during the transition. Manure production of an animal is directly related to milk production and dry matter intake. Higher milk production stems from higher dry matter intake of animal and results in increased manure production. A farm that once produced 60 pounds of milk per animal per day may decline to 30 lbs. of milk per animal per day in grass-fed production and thus will produce 26 pounds less manure per animal per day (Figure 11).

In addition, nutrient concentrations in manure will change. The less grain fed, the lower the nutrient concentration in the manure will be. As seen in Figure 12, dairy animals that are fed conventional diets, which often include higher levels of grain, generally have higher nutrient concentrations in their manure. As farms transition to organic, less grain is generally fed to animals due to cost, animal health, and changing milk production goals. In grass-fed systems, with no grain at all, nutrient concentrations in manure can drop by 50%. Although grain is a costly input, it helps provide valuable dry matter, nutrients, energy, and protein to cows, supplementing the forage available on the farm. Nutrients not utilized by the animal make their way into the manure and back on to the fields. This nutrient input no longer exists on a grass-fed dairy. Purchasing forage is an option and could serve as a valuable input to the farm. Otherwise, it is likely that purchasing external fertility sources will be necessary to maintain the productivity and quality of the forages.

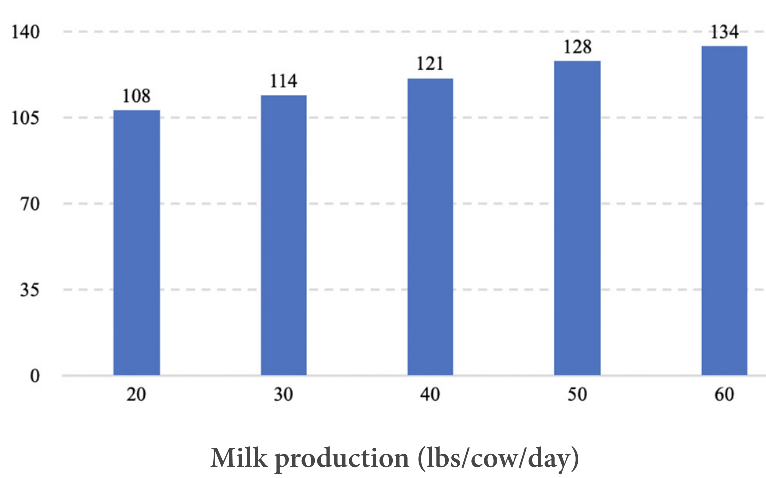


Figure 11. Manure production (pounds per animal per day) as influenced by the level of milk production (pounds per animal per day).

Source: Heather Darby, UVM Extension

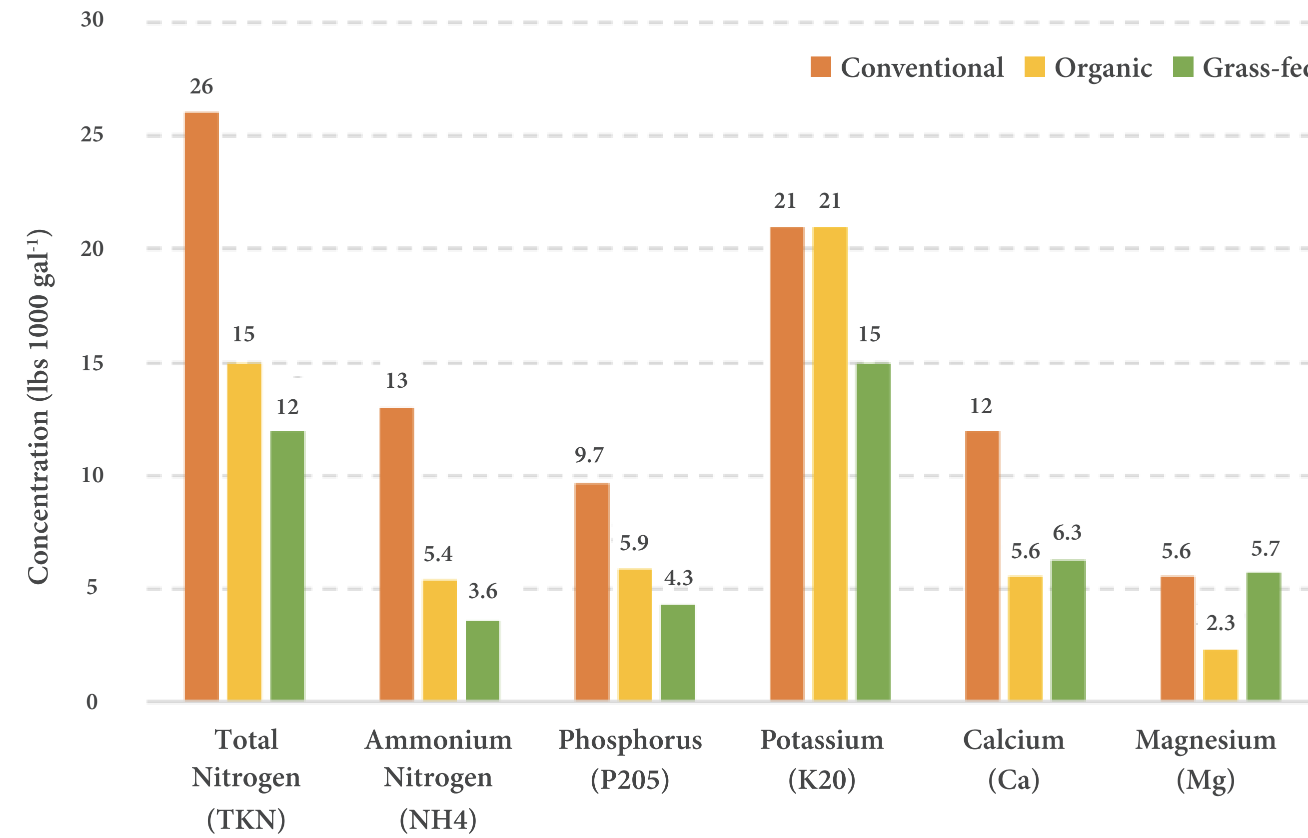


Figure 12. Nutrient concentration of manure from different farming systems feeding different amounts of grain.

Source: Heather Darby, UVM Extension

Whole Farm Nutrient Balancing: Unique Challenges for the Grass-fed Dairy

Although balancing nutrients in soil is important, it cannot be considered in isolation from the nutrients and composition of other components of the farm. This is called Whole Farm Nutrient Balancing. Whole farm nutrient balancing is essentially like balancing a checkbook of nutrients coming onto and leaving the farm. Farms import (or deposit) nutrients through purchased feed, bedding, fertilizers and other soil amendments, minerals, and imported manures. Farms export (withdraw) nutrients from the farm through the sale of animals, milk/meat, crops, and other products. Issues can arise when there is a severe imbalance between imports and exports, especially over long periods of time. If more nutrients come on to the farm than leave, nutrient levels in soils will continue to rise and ultimately may pose risks to the environment. On the other hand, if more nutrients leave the farm than are imported, soil fertility will decline and ultimately crop, and animal productivity will suffer.

On most dairy farms, large quantities of nutrients (like phosphorus and trace minerals) are brought onto the farm in the form of grain. The grain is fed to cows, adding nutrients through the farms' manure supply, which then is spread on the land used to produce forages. Eliminating the import of grain nutrients in a grass-fed system without a clear plan to maintain soil fertility leads to depleted soil nutrient levels and, consequently, poor forage productivity and quality. In addition, due to increased land needs to support a grass-fed herd, grass-fed farms may have less manure to spread per acre, further depleting soil nutrient reserves if additional fertility is not imported. This is often exacerbated by the fact that available organically approved fertilizer options are limited and often considerably more expensive than conventional options. Understanding the implications and costs of nutrient imbalances is crucial to long-term success of farms. Since forage production and quality can fluctuate significantly, poor nutrition poses numerous risks to the herd and farm economics. Therefore, it is critical to identify significant nutrient deficits and address them before they negatively impact the farm. To maintain productivity of animals and land, changes to nutrient imports and exports must be evaluated as a farm considers transition to grass-fed and then monitored over time.

Let's dig into this a bit more with three examples evaluating the whole farm nutrient balance: first of an organic farm, second of a grass-fed farm with purchased fertility, and third of a grass-fed farm with no purchased fertility. In the first example, an organic dairy is feeding grain and buying forage. Exports from this farm are primarily from milk but also some from cull cows and compost sales. As seen in Table 11, the farm is operating in a slight nutrient excess, with nitrogen (N), phosphorus (P), and potassium (K) accumulating each year.

Organic Farm Whole Farm Nutrient Balance	N	P	K
Imported (tons) Grain, Baleage, bedding Minerals	5.64	1.00	3.57
Exported (tons) Milk, Meat, Compost	2.66	0.45	0.71
Balance (tons)	2.98	0.55	2.86
lbs./hundredweight (CWT)	0.87	0.16	0.84
lbs./acre	56.8	10.5	54.5

Table 11. Example of a whole farm nutrient balance in tons of nitrogen, phosphorous, and potassium on an organic dairy farm (48 cows, 20 replacements, 105 acres) that feeds grain.
Source: Heather Darby, UVM Extension

In comparison to a grass-fed dairy, more than double the acreage is required to feed a similar number of cows. Since there are no grain imports in grass-fed production, fertility is brought on to the farm in the form of poultry manure. As shown in this example, the quantity of imported nutrients is low and nearly all from the poultry manure. The level of exported nutrients exceeds the nutrients coming on to the farm (Table 12). In the third example, the same grass-fed farm does not import poultry manure to fertilize, and consequently all nutrients are at a deficit (Table 13).

When evaluating whole farm nutrient balances, these types of imbalances can be helpful at times (for example, to draw down high soil P), but long-term draw down of nutrients is harmful to production. Evaluation of whole farm nutrient balances is critical to monitor and balance nutrient flows on the farm.

How to avoid these pitfalls? Farmers should start by evaluating the soil nutrient levels through conducting basic soil samples and calculating the whole farm nutrient balance to develop a baseline. The "Whole Farm Nutrient Mass Balance Calculator" developed by Cornell University is an easy-to-use tool intended to help identify opportunities for improvements on dairy farms. Farmers should monitor yields and fertilize (starting with manure) to achieve yield goals. Fertility needs of forages can be quite substantial, depending on the desired yield. In stands that consist primarily of grass, every ton of dry matter will require 50 lbs. of N, 17 lbs. of P, and 50 lbs. of K. And the more dry matter harvested per acre, the higher the nutrient needs of the crop.

Nutrients and amendments should be applied to meet a realistic yield goal. Manure is a complete fertilizer and contains all 13 nutrients that the plants require. However, to provide this level of nutrients, a substantial amount of manure must be applied and may limit the number of acres that can be spread. Further, with lower quantity and quality of manure, it is pertinent to think about other nearby sources of fertility. Accessing manure from other farms might be a cost-effective option to maintain P, K, and other nutrients. To meet N demands of grasses, legumes should be incorporated into the cropping system. As seen in Table 14, mixed stands can produce higher yields of forage and replace the need for supplemental N additions. Practices such as frost seeding or using a no-till drill to add seed on a regular basis can help maintain legume levels. Although there are many factors and practices that influence forage quality and quantity, soil fertility and health are primary drivers that will require monitoring and investment to be successful with grass-fed dairy.

Grass-fed Farm Whole Farm Nutrient Balance	N	P	K
Imported Fertility Poultry manure, minerals	0.08	2.06	0.8
Exported (tons) Milk, Cull Cows	1.83	0.34	0.53
Balance (tons)	-1.03	1.72	0.27
lbs./CWT	-0.32	0.53	0.08
lbs./acre	-8.62	14.32	2.27

Table 12. Example of a whole farm nutrient balance in tons of nitrogen, phosphorus, and potassium on a grass-fed dairy farm (48 cows, 40 replacements, 240 acres) that imparts fertility.
Source: Heather Darby, UVM Extension

Nitrogen Treatment	DM Yield Tons/acre
N Fertilizer	1.25
Grass-Legume Mix	1.28
Grass Alone	0.607

Table 13. Grass yield from one harvest when grass is grown with N fertilizer, with legume, and alone.
Source: Heather Darby, UVM Extension

Grass-fed Farm Whole Farm Nutrient Balance	N	P	K
Imported (tons) Minerals	0	0.51	0.05
Exported (tons) Milk, Cull Cows	1.83	0.34	0.53
Balance (tons)	-1.83	0.17	-0.48
lbs./CWT	-0.57	0.05	-0.15
lbs./acre	-15.3	1.41	-3.98

Table 14. Whole farm nutrient balance of a grass-fed dairy farm (48 cows, 40 replacements, 240 acres) with no imported fertility.
Source: Heather Darby, UVM Extension

Example: Nutrient Management to Meet Forage Needs

In the chapter on forage management, an example looked at a farm milking 60 cows on 170 total acres, including pasture that yielded 1.75 tons of DM/acre and hay fields that yielded 2.5 tons/acre. This would produce a total of 373 tons of DM/year from hay and pasture. The forage intake needs for the whole herd, including youngstock, was 550 tons of DM/year, so the farm was short 177 tons of DM per year.

If the farm could improve soil fertility and soil health to increase yields in the pasture to 2 tons of DM/acre and up to 3 tons/acre in the hay fields, then the farm would only be short 110 tons of DM per year. Though the farm would need to purchase more fertility inputs, it would avoid the expense of buying 67 tons of DM forage, the equivalent of about 268 round bales, each year.

Raising yields by 0.5 ton per acre is achievable and, on a basic level, could be accomplished through evaluating soil fertility needs and likely adding legumes to boost yields. The cost of nutrients to gain this level of yield would include an additional 25 lbs. N, 10 lbs. P, and 25 lbs. K.

The farm will need to purchase feed to meet remaining nutrients, but splitting expenses between purchased feed and soil management may prove to be a good investment. The purchased forage will allow nutrients to be brought onto the farm and further build fertility while also providing nutrition to the cattle.

KEY POINTS

- **Soil pH** is a measure of the acidity or alkalinity of the soil: neutral = 7, acidic soil < 7; basic or alkaline > 7. Most agricultural crops experience optimal growth at a pH of 6 to 7.
- To **minimize erosion**, ensure fields have sufficient vegetative cover and avoid over grazing.
- **Soil tests** identify current nutrient levels in the soil, thus indicating deficiencies requiring soil amendments and/or management changes.
- A healthy, fertile soil should exhibit high soil organic matter content, high biological activity, good soil tilth, minimal erosion, proper pH, and balanced nutrients.
- Tracking all nutrients coming onto and leaving the farm through a tool called **whole-farm nutrient balancing** can be used to ensure adequate soil fertility.
- In the transition from conventional to grass-fed production, the elimination of grain nutrient imports and the increase in land needs per cow can lead to soil nutrient depletion and poor forage productivity/quality if not intentionally managed.

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