

Abstract

The notion that fertilizers must be water soluble for *passive* uptake by plant roots is inconsistent with the processes of nature. There is actually very little, if any, dissolved plant nutrients in well-balanced natural soil solutions of productive soils. High concentrations of dissolved “plant food” are not typical of natural soil systems. For example, there is only about 1 pound of soluble nitrogen in an acre of soil solution under natural conditions. When highly soluble plant food is applied to living soil systems in quantities typical of high-input agriculture, they disrupt the complex relationships among microbes, plant roots, soil organic matter, and minerals, resulting in lost profits and extensive damage to the entire ecosystem. There is a place for soluble inputs in agriculture, but their use must be limited as they have a propensity to contaminate the soil and water environments. The use of highly soluble fertilizers creates conditions that are remarkably similar to human drug addiction¹; continued use only leads to further dependence on synthetic fertilizers and pesticide intervention.

Fortunately, numerous ecologically sound practices have emerged recently. The evolution of new bio-compatible inputs for sustainable agriculture meet more demanding standards than simple solubility. In fact, they generally ignore water solubility, making them fit for the purpose of life. Mineral inputs used in ecologically sound agriculture have to be geochemically complex as well, making them more compatible with the geological cycles of soil ecosystems that support an extremely complex underground living ecosystem. Additionally, they must have surface structures that are compatible with the complex soil carbon compounds released by plants and microbes; synthetic chemicals cannot meet those requirements.

Regenerative farming practices emphasize nutrient acquisition from soils through natural soil biological cycles. Essentially, these ecologically-based agricultural approaches integrate with the living *carbon cycle* as part of crop production instead of relying entirely on highly soluble nutrient inputs for plant nutrition.

Soil microbiology interacting with plant roots and soil minerals releases plant nutrients from minerals. The biological release of plant nutrients has far greater potential to release nutrients for plant uptake² than simply relying entirely on soluble nutrients as the sole source of plant nutrition. Unfortunately, since the invention of the Haber-Bosch process in 1909, which is an energy intensive process developed for warfare that combines nitrogen (N_2) with hydrogen (H_2) to make ammonia (NH_3), is the basis of synthetic nitrogen fertilizer chemicals.

Historically, soil microbes have been responsible for providing about 80% of all the agricultural soil nitrogen through the very efficient process of microbial nitrogen fixation.³ However, soil compaction and over-use of nitrogen fertilizers are having a dramatic negative impact on nitrogen fixing microbes. For the first time since the Earth was created, the total fixed nitrogen supplied by microbes is actually less than the amount of applied synthetic nitrogen.⁴

Plants have devised complex systems of breaking down minerals into nutrients and then using *active transport* mechanisms to move them through their roots. Although *active transport* of some nutrients is mentioned in some conventional agricultural textbooks, no mention is made of the fact that biological activity and complex organic substances are critical components driving the efficiency of the process. If you look upon soils as living ecosystems instead of a place to force production through genetic manipulation and synthetic chemical intervention, you will discover there are other ways to feed plants in nature's image that are efficient, profitable, and ecologically sound.

Nitrogen is not applied to improve the quality or fertility of soils; instead it is used, as one Amish farmer said, as a synthetic plant growth stimulant. Over application of highly soluble synthetic materials is essentially the “root of all evil” in agricultural systems. In countries where crops are heavily subsidized by governments, nitrogen use efficiency is very low. Where subsidies have been decreased or removed, nitrogen use efficiency has improved significantly. Currently, the US wastes about 54% of all the nitrogen applied to corn crops.⁵

Aqueous Solubility: The Foundation of “Plant Food”

The amount of a substance that will dissolve at a given temperature in a specific amount of water is known as its *aqueous solubility*. In order to be soluble in water, a substance must be capable of easily *dissociating* (breaking up) into positively charged ions (cations) and negatively charged ions (anions).

The guaranteed analysis for selling plant food is based on commodity pricing and government regulation, which has nothing to do with the behavior of fertilizers in soils, and completely ignores environmental sustainability. By chemical definition, in order to be highly soluble in water, fertilizers must easily dissociate in water into highly charged positive ions (cations) and negatively charged ions (anions). “Salts” of chemical reactions are the simplest, but the most wasteful and ecologically damaging way to accomplish this.

Fertilizers are actually categorized by their *salt index*, which is a ranking of the potential to injure germinating seeds and plants. The salt index of a fertilizer is directly related to its water solubility. The so-called “burn” to plant roots is actually caused by dehydration of the soil, which is a natural reaction by soils to counteract high salt inputs. Other soil reactions to highly soluble fertilizers are “leaching” and becoming “tied-up” to soil colloids. All of which are reactions by soils trying to maintain chemical *equilibrium*, starting immediately after application, resulting in a dramatic reduction in the quality of the living soil system that eventually harms plant health, soil health, and ultimately human health.

Fertilizer Regulations

Soluble fertilizers are supposed to deliver “plant food” to the plant roots through *mass flow*, *osmosis*, and *diffusion*; essentially treating soils as hydroponic solutions, with complete reliance on soil water solution to deliver nutrients to plant roots. The solubility percentages for Nitrogen, Phosphorus, and Potassium (NP&K) on fertilizer tags are supposed to be “available” plant “food”, which is a shamefully over-simplified approach to soil fertility. For example, a 9-18-9 fertilizer gives the impression that 9% nitrogen, 18% phosphorus, and 9% potassium represents the portions of the product that are “available” plant food; however, aside from the nitrogen guarantee which will be addressed later, the guarantees for phosphorus (P) and potassium (K) are misleading (see side bar).

As a condition for selling synthetic fertilizers in the US, fertilizer manufacturers are required to declare the “guaranteed” amount of soluble nitrogen, phosphorus & potassium, i.e. N, P & K.

The NP&K values on fertilizer labels are misleading, because NP&K are not minerals, they are elements, and the chemicals guaranteed on a fertilizer label are actually mathematical conversions to theoretical chemicals that represent data generated under laboratory conditions. The regulatory terms for these chemicals are called “available plant food”, they are not the natural products found in living breathing soils.

The guaranteed analysis on a fertilizer label does not reflect what happens when the chemicals are applied to soils, where every aspect of soil chemistry is not duplicated under laboratory conditions, especially the *bioavailability* of the applied nutrients. As a general rule, all of the soluble NP&K in a fertilizer becomes “tied up” in the soil matrix within a few days after application. This occurs because high

Guaranteed Analysis

The phosphorus (P) guarantee on a fertilizer label is actually diphosphorus pentoxide (P_2O_5) and the potassium (K) is actually K_2O , both of which are considered oxide “equivalents” strictly for the purpose of conveniently calculating the analysis based on pre-20th century laboratory procedures. Neither chemical is present in a fertilizer.

concentrations of soluble chemicals need to be brought into chemical equilibrium⁶ in the soil system, otherwise they are potentially toxic to plants and absolutely toxic to the microbial population, which ironically are ultimately responsible for delivering bioavailable nutrients to plants regardless of the form of the input.

In reality, the *guaranteed analysis* of NP&K (such as 9-18-9) on a fertilizer tag is derived from rudimentary laboratory procedures that are supposed to represent the portions of a fertilizer that are plant “available”. But, the numbers actually represent the relative quantity of chemicals that have been dissolved by chemical reagents (not microbes) and then recovered from solution under laboratory conditions; conditions that are specific only to a particular analytical protocol used strictly for regulatory purposes within a particular state. In reality, each state has adopted its own analytical procedures, which may or may not be the same as those used by other states or by commercial labs serving agriculture. And, some states are using analytical procedures that have not been *validated* by the scientific community; meaning they are not fit for the purpose intended.

Solubility and Biochemistry

Soils are the most complex living ecosystems on the face of the Earth, which has not been duplicated under laboratory conditions. As such, they need to be respected and understood as living systems that are sensitive to highly soluble salt inputs.

In *low input* (sustainable, biological, organic, regenerative) agriculture, highly soluble soil inputs are used sparingly, and insoluble inputs, such as rock phosphates, are used to correct soil fertility, avoiding the disruptive effects of salt-based fertilizers. The disruption from salts is dealt with primarily by water, which changes from a highly structured molecule (order) to that of hydrated solvation complexes (disorder) to neutralize the high cation and anion charges on the fertilizers,⁷ removing valuable energy from the soil system during the process.

The water in soils contains both dissolved and un-dissolved substances in it. The portion of soil water with dissolved substances is called the *soil solution*. Table 1 illustrates the concentration of plant nutrients that are typically found in soil solution. The concentrations of soil nutrients are listed in mmol (millimoles) of dissolved material per liter of water (mmol L⁻¹). A millimole is 1/1000th of the molecular weight of a substance expressed as its weight in grams. For example, the molecular weight of nitrogen is 14. If 14 grams of nitrogen were capable of dissolving in one liter of water, that would be 1 mole of nitrogen. One millimole of nitrogen is 0.014 grams.

Using the highest value for nitrogen in Table 1, the average concentration of nitrogen was 0.46 mmol L⁻¹. Converting the molar mass data to pounds per acre requires making assumptions about the volume and weight of water per acre, thus introducing a great deal of variation into the calculation. However, no matter what assumptions are made, the total nitrogen dissolved in soil solution per acre is in the range of approximately 0.4 to 1.5 pounds per acre. For dissolved phosphorus, the range would be 0.001 to 0.003 pounds in one acre! Just a trace.

Table 1. Median Concentration of Nutrient Elements in Soil Solutions

Nutrient	mmol L ⁻¹	mmol L ⁻¹	ppm
Nitrogen (total)	0.46	0.014	0.05
Phosphorus	0.0004	0.0002	0.005
Sulfate	0.18	0.16	1.67
Potassium	1.28	0.09	3.5
Calcium	1.87	0.8	32
Magnesium			25

Modified from; Cacco, G. and Varanini, Z., 2003. Scarponi, L., (ed.), *Biochimica agraria*, Patron, Bologna, p. 837;

Wolt, J.D., 1994. *Soil Solution Chemistry*, John Wiley & Sons, New York, p. 218; Bowen, H.J.M., 1966. *Trace Elements in Biochemistry*. Academic Press, London, pp. 31-32.

If it takes 1 pound of total elemental nitrogen to grow 1 bushel of corn conventionally, or 150 lbs of total N to grow 150 bushel of corn per acre, and if there is only about 1 pound of N per acre naturally in soil solution, where does the nitrogen come from?...the answer is biological fixation of nitrogen from the atmosphere and the numerous organic compounds produced from biological activity.

As you are reading this, you are breathing in almost 80% nitrogen....plants and soil microbes do the same, but instead of treating nitrogen like an inert chemical, soil microbes utilize it. Look at any chart of the Nitrogen Cycle of plants; you'll see where numerous biological soil interactions are the primary steps in the cycle supplying plants' nitrogen needs....yet the interactions of microbes supplying nitrogen to plants through various soil microbial processes and the creation of organic nitrogen compounds as nitrogen sources are almost totally ignored in conventional education. Additionally, soil compaction, which robs soil microbes of needed oxygen and nitrogen, destroying the opportunity to reduce N inputs and reducing crop diseases, is not even addressed in a typical college text book on soil fertility and fertilizers.⁸ In fact, the only mention of microbes in the index of this current college book is a brief mention of the "tie-up" of phosphorus by microbes. The word fungus does not appear in the index and bacteria are mentioned on one page only.

When highly soluble fertilizers are applied to a soil, the soil system will fight back with every resource it has to achieve chemical and biochemical equilibrium. If you have ever tried drinking a glass of water that has a teaspoon of table salt dissolved in it, you know what I mean. If you don't vomit, you will at least get an upset stomach and will be extremely thirsty for a long time. Salt fertilizers will either leach out or use large quantities of water to offset the high salt inputs.

Hydrophobic Interactions

Every living thing in our universe is governed by *biochemical* reactions that occur at extremely low concentrations of dissolved ions in water, where almost all biological reactions proceed under conditions that shun water (hydrophobic conditions). However, conventional agriculture has taken the opposite approach by assuming that soils need highly soluble fertilizers, called "plant food". This approach is primarily driven by the fertilizer manufacturing sector in concert with state fertilizer regulators.

Interactions in soils that release plant nutrients are biochemical, not just chemical. Almost every biochemical reaction and interaction occurs under *hydrophobic* conditions.....where water is shunned. The *hydrophobic effect occurs* when enzymes and microbes work together to make surface adhesion and the energy available to do "work" the dominant life forces, not water solubility!⁹

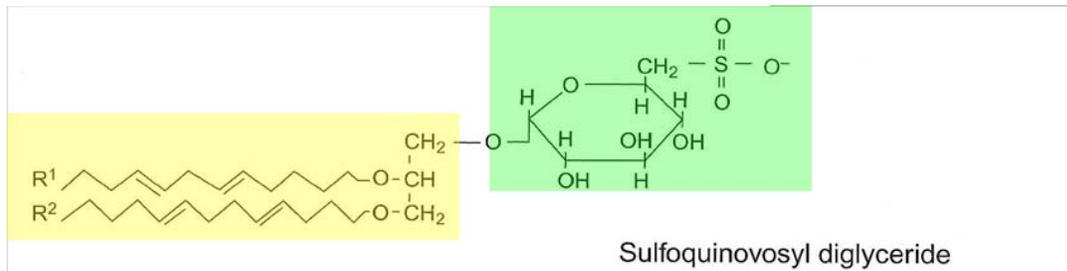
In stark contrast to the substantial amount of energy to stabilize highly soluble materials, hydrophobic interactions allow insoluble nutrients to cross through living membranes in a manner that utilizes the least amount of energy. Therefore, the *bioavailability* of a nutrient, such as calcium, is not totally dependent on water solubility alone, because in nature it would be far too inefficient. Nature works smart, not hard.

The photo of water droplet on a leaf illustrates one of the most common hydrophobic effects; a water repulsed by a leaf membrane. The same repulsion of water by membranes occurs on your skin, in all living cells, and microbial interactions in soils. The movement of water and nutrients across living membranes does not occur in a helter-skelter fashion; the movement of substances across living membranes is a highly regulated multidimensional process.



Biological membranes use mechanisms that incorporate enzymes, integrated membrane proteins (IMP), and other *amphiphilic* molecules to move nutrients through living membranes. Amphiphilic molecules have both hydrophobic (water shunning) and hydrophilic (water loving) domains in their molecular structure. All humic substances, many proteins, and most soil sulfur compounds (Figure 1) are amphiphilic.

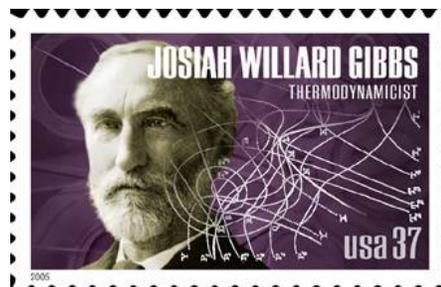
Figure 1. Example of a hydrophobic sulfur compound



Thermodynamics

$$\Delta G = \Delta H - T\Delta S$$

The study of thermodynamics started around the year 1820 out of the desire to increase the efficiency of steam engines. By the 1840's, scientists began linking thermodynamic principles to chemical reactions to help predict how substances would interact energetically. The laws of thermodynamics were first laid down by the American physicist Josiah Willard Gibbs, who published a series of three papers, the most famous being *On the equilibrium of heterogeneous substances* in 1876. Gibbs demonstrated how thermodynamic processes, including chemical reactions, could be mathematically and graphically analyzed. By studying the total energy in a system that is available to do work (enthalpy), disorder (entropy) and chemical potential of a thermodynamic system, Gibbs could determine if a chemical process would go forward, or not. The same thermodynamic principles can be used to predict whether a soil input will work, regardless of whether it is being used as a conventional fertilizer or within the guidelines of regenerative agricultural practices.



If a soil chemical reaction is not thermodynamically favorable, the reaction will not occur. That means soil biology can't make a thermodynamically unfavorable chemical reaction go forward either.¹⁰ Thermodynamically, highly soluble fertilizers are disruptive to the energy flows of soil systems, expressed as *disorder*. The disorder caused by highly charged positive and negatively charged (soluble) soil inputs is reduced by surrounding the charged anion or cation with a shell of water molecules¹¹ to neutralize the ionic (electrostatic) charge of the offending chemical species. This chemical mechanism is called *ion hydration*, which is favored thermodynamically as a means to insulate the strong ionic charges on salt fertilizers, and can be calculated as the *enthalpy of hydration* (ΔH_h). See Table 2.

Table 2. Enthalpy of Hydration for Select Cations and Anions

Ion	ΔH_h kJ mole ⁻¹
H ⁺	-1091
K ⁺	-321
Cl ⁻	-363
NO ₃ ⁻	-328
Ca ²⁺	-1592
SO ₄ ²⁻	-1145

Modified from Essington, 2004. Soil and Water Chemistry, CRC. P. 186.

For example, potassium chloride (KCl), also known as potash or 0-0-60 is a common soluble fertilizer ingredient. In water, it dissociates into positively charged cations (K⁺) and negatively charged anions (Cl⁻). The negatively charged chloride anion (Cl⁻) has a disruptive effect on the soil water solution expressed as $\Delta H_h = -363$, which is a measurement of the energy required to chemically stabilize the ionic charge by water of hydration (insulation). The K⁺ cations have a $\Delta H_h = -321$ in 0-0-60, which means K⁺ also needs stabilizing through hydration.

Chlorides (Cl⁻) and other highly soluble (unstable) chemical species, such as sulfates (SO₄²⁻), nitrates (NO₃⁻), disturb the structure of soil water¹², so they must be stabilized (detoxified) by the soil system. The disturbance they cause can be explained thermodynamically as an increase in *entropy*, or disorder.

The more negative the ΔH_h , the greater the disruption to the soil water solution; greater disruption means more energy must be used to stabilize the disruption, which is less energy available for plants and microbes to their work. Note how hydrogen (H⁺) proton (Table 2) has one of the highest ΔH_h values; it is responsible for soil solution acidity (expressed as pH).

Perhaps the removal of energy from soil systems as part of the hydration of fertilizer ions is one more reason why conventional agricultural systems with high concentrations of salt (electrolyte) fertilizers need heavy irrigation to make a crop. Many of these thermodynamic problems can be overcome by building soil organic matter and humic substances, both of which play an important role in bringing more order to biological systems, essentially stabilizing many potentially toxic chemical species.¹³

Gypsum

There is also a movement in regenerative agriculture towards increasing the total percentage of soil calcium saturation by using calcium compounds. Agricultural gypsum, which is primarily composed of calcium sulfate dihydrate (CaSO₄•2H₂O), is marketed as a soluble calcium input that is supposed to have no effect on soil pH, in contrast to limestone. However, for every soluble gypsum calcium ion (Ca²⁺) applied to the soil matrix, each calcium ion will become associated with six water molecules in order to stabilize the substance. Therefore, it makes more sense to use moderate to low concentrations of calcium Ca²⁺ in solution to conserve more energy to do work. The dehydrating effect of highly soluble calcium

compounds is demonstrated by the damage done from applying too much calcium oxide (CaO) or calcium hydroxide (CaOH), referred to as “burning”.

Gypsum is considered to be a highly soluble agronomic form of calcium and sulfur, typically recommended to mobilize soil magnesium. However, the ΔH_f of sulfate (SO_4^{-2}) is -1145, which indicates sulfates are highly disruptive to soil solution. That’s one reason why inorganic sulfates rarely exist in natural soil systems (Table 3); instead almost all soil sulfur is organically bound,^{14,15} meaning it is associated with carbon, typically as amino acids and proteins (Figure 1).

With continued yearly application, it is likely that gypsum can become over-applied on many farms. It is well-known that gypsum can release calcium Ca^{2+} and sulfate SO_4^{-2} into soil solution, and it has been established that calcium and sulfur can be antagonistic to many major nutrients and micronutrients, especially magnesium and manganese,¹⁶ but there is very little research on that effect. There are unpublished reports that gypsum converts soil magnesium and manganese into less bioavailable species, confirmed by analyzing plant tissue samples from field trials.

Perhaps the relatively large quantities of magnesium mobilized by gypsum can cause an imbalance with other nutrients. The antagonistic effect of excessive soluble soil magnesium in combination with excess sulfate on micronutrient bioavailability is generally not well known. However, it has been established that excessive magnesium interferes with the absorption of zinc, copper, iron and particularly, manganese.¹⁷ Also, some field observations confirm that using gypsum alone as the sole source of calcium has a depressing effect on the plant uptake of zinc, iron and manganese. It is well established that the suppression of manganese uptake in crops treated with glyphosate herbicide causes more plant disease.¹⁸ So, the use of gypsum on GMO crops engineered for glyphosate resistance may actually compound the negative effects of glyphosate.

Figure 1. The composition of soil organic sulfur

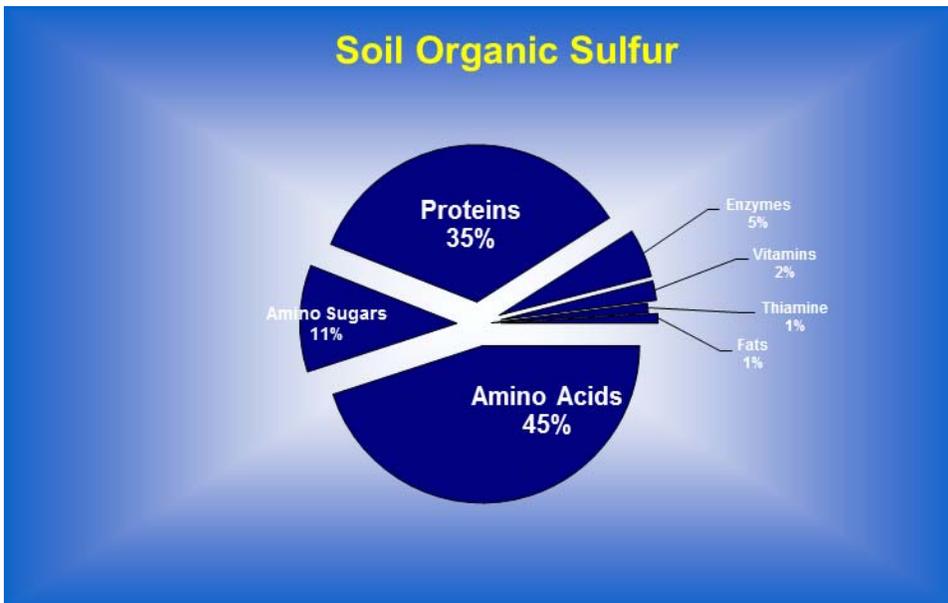


Table 3. Soil sulfur

Soil texture	Organic C (g kg ⁻¹)	Total Sulfur	SO ₄ ⁻² (mg g ⁻¹)	Organic S (mg g ⁻¹)
Silty clay	43.3	467	17.8	449
Silty clay	39.7	531	10.6	520
Silty clay	8.2	154	3.3	151
Silty clay	32.2	545	6.0	539
Sandy	49.5	652	3.3	648
Sandy	44.6	582	6.3	576
Silty	34.5	338	4.6	333
Silty	26.5	282	16.8	265

Adapted from Zhao et al., 2006. Sulphur speciation and turnover in soils. *Soil Biology & Biochemistry* 38:1000-1007.

The Structure of Water

The *structure* of water can be disrupted from its natural state in soil systems by the over application of highly soluble inputs. Water actually exists in a number of configurations, each one determined by the influence of surrounding chemicals that either bond with it or influence it through other mechanisms. The structure of water, which vibrates at a frequency of 1×10^{12} times a second¹⁹, is constantly changing its structure, and is often described as two hydrogen atoms located on an oxygen atom at an angle of 104.45° to each other (Fig. 2).

However, the configuration in Fig. 3 only exists when water is in the “free state”, which only occurs as a gas (steam), where it is separated from other substances that influence its structure, including itself. Water molecules in the *free state* with no impurities are separated sufficiently from each other so as to not influence their physical character through what is called *hydrogen bonding*. The liquid water that we are accustomed to owes its unique properties to hydrogen bonding, which lines up water molecules according to the weak charges that exist on each water molecule (Fig. 3).

Figure 2.
An isolated water molecule (steam)

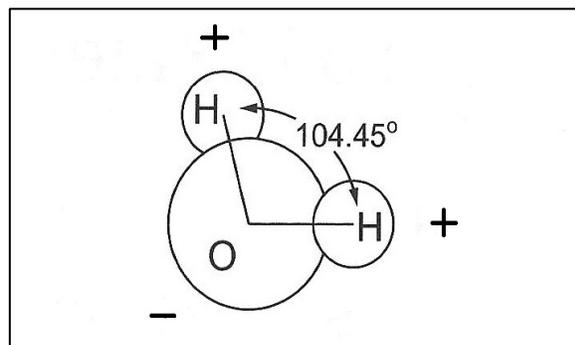
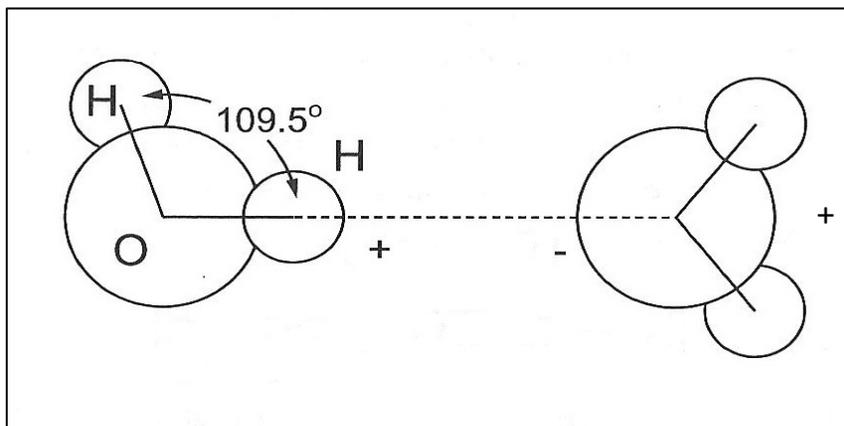


Figure 3. Water molecule in the liquid state



Hydrogen bonding creates slight negative and positive charges on each water molecule (dipoles), making it cohesive. This explains why water is a universal solvent and a carrier of plant nutrients in soil solutions, and simultaneously adhesive, more or less sticking to itself. Under these normal conditions, the angle of the hydrogen atoms on the oxygen atom is 109.5° , but when an electrolyte is introduced, such as a high salt index fertilizer, the normal attractive forces between water molecules is disturbed, thus increasing disorder.⁹ The stabilizing reaction, *enthalpy of hydration*, is the energy removed from the soil system to create more order; energy that might well be used for plant growth and protection, rather than detoxifying a chemical input. In other words, the *quality* of the water applied to soils depends on whether a highly soluble or a low soluble product has been applied: the lower the solubility, the higher the quality of water.

Life-enabling water structures in the aqueous interphase, the area between microbes and soil colloids, is normally maintained by weak electrostatic fields and the heparan sulfate proteoglycans that make up cell membrane surfaces, can be disrupted by strongly charged ions, such as aluminum cations (Al^{3+}), chlorides (Cl^-) and sulfates (SO_4^{2-}). This disruption leads to localized “unwetting”, increased water tension, and cell membrane “softening.” In the case of cationic aluminum (Al^{3+}), it ties up the cell surface charges. Cell surfaces may consist of complex carbohydrates that undergo surface charge neutralization when too much Al^{3+} is present in water, thus breaking up the carbohydrate-membrane electrostatic connection between the exterior of the cell matrix and the interior components. The resulting “short circuits” have several adverse consequences, including impaired electrical conductivity of the cytoskeleton and microtubules that support the cell structure and disorientation the cell membrane structure, which can accelerate the abnormal cell division, similar to what happens to human cells that are cancerous.²⁰

Optimal surface charge density among soil colloids and microorganisms, thus allowing for better “communication” between biology, minerals, and soil colloids is critical. The crystalline surfaces of soil minerals send out what is called a *diffuse electrical double layer* of charge into the soil water solution. The way microbes and organic matter interact with these double layers of charge determines the efficiency of their life processes.²¹

Just as almost all soil colloids carry an overall negative charge on their surfaces, microbes are also negatively charged.²² As a general rule, microbes that have plenty of nutrition also have the ability to adhere to surfaces better than microbes that are undernourished. Well-nourished bacteria demonstrate the highest degree of hydrophobic character and carry a relatively higher negative charge than undernourished bacteria. Their ability to adhere to like charged soil surfaces seems contradictory because like charges repel. However, due to their increased hydrophobicity, they overcome the repulsion through a physical interaction force called *van der Waals attraction*.²³

van der Waals attractive forces are extensively exploited in nature. For example, spiders have scopula pads on the ends of their legs that utilize these weak van der Waals forces, enabling them to climb or hang upside-down from extremely smooth surfaces such as glass or porcelain. Although the forces are sufficient to allow a spider to “stick” to surfaces, the weakness of the forces is easily demonstrated by the way spiders have no difficulty overcoming the forces when walking and the way they can be easily swat down from any surface.

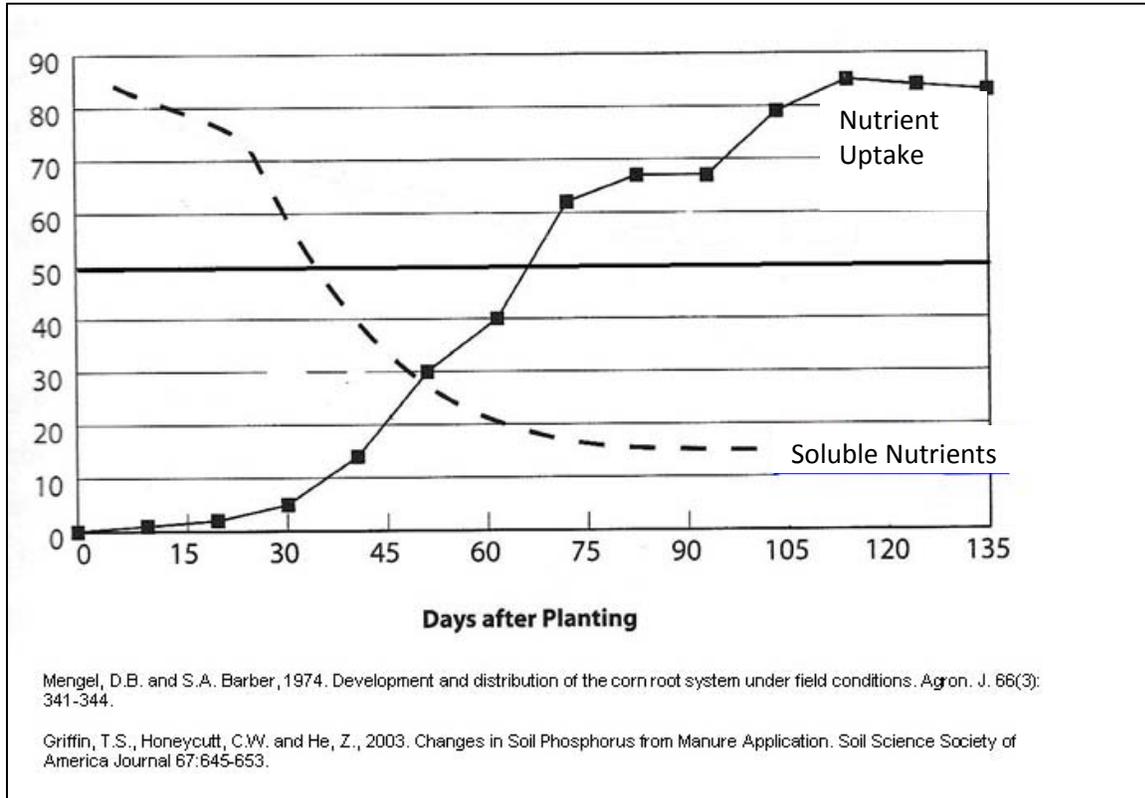
Because van der Waals attractive forces are not electrostatic, they are easily overcome by the presence of high concentrations of soil solution cations. It is likely that any excess of positively charged cations in the soil solution will cause a reduction in the hydrophobicity and van der Waals forces, interfering with the process of adhesion.²⁴

Nutrient Tie-Up

As well as more water usage, the net effect of the thermodynamic flows described above can be expressed in terms of *fertilizer tie-up*. All highly soluble synthetic soil inputs, even highly soluble calcium, will become tied-up in the soil matrix over relatively short lengths of time, as illustrated in Fig. 4. While the soluble nutrients applied at the beginning of the planting season become less and less “available”, the plants’ requirements for nutrients are increasing. Conventionally, the problem of plants not getting

enough nutrients later in the season is solved by applying more fertilizer. Obviously this over application of nutrients is very harmful to the environment and the bank account.

Figure 4. Soluble Nutrients in Soil Solution after Application



Activation Energy

Just because a reaction is thermodynamically favored, it doesn't mean the reaction will occur, releasing plant nutrients. The chemical reaction has to be *kinetically* favored also. For example, if a rusty nut refuses your efforts to break loose from a rusty bolt, you can increase the force on the nut by using a longer wrench or breaker bar, essentially changing the kinetics of the procedure, and probably breaking the bolt. But, if you apply penetrating oil on the nut, you decrease the amount of energy needed to break the nut loose. The penetrating oil helps with the process but does not enter into a chemical reaction with the wrench.

The burning of wood provides another example of how reactions must be kinetically favored. Wood contains carbon in a state that lends itself to oxidation. When burning, it releases large amount of energy, the reaction with oxygen is said to be thermodynamically favored because of its (exothermic) nature to release energy upon oxidation and the high stability of the end products; carbon dioxide and water. But if you try to light a large chunk of wood with a match, it won't catch fire because the activation energy requirement to oxidize the large surface is very high compared to the size of a match; so scientists say the reaction is not favored *kinetically*.

Energetically, the examples above are somewhat similar to the way biological systems have developed ways of lowering the *activation energy* of biochemical reactions; otherwise the amount of energy needed to break chemical bonds to release plant and microbial nutrients would be overwhelming. For example, nature has figured out how to make two or more chemical reactions happen at the same time, essentially taking energy from the simultaneous "making and breaking" of chemical bonds, instead of needing huge amounts of energy if the process was done one at a time.²⁵ This is especially true for phosphorus as the ultimate biological energy transfer agent in living systems.

The super efficient transfer of energy in living soil systems is accomplished by the synergistic activities of plants and microbes in the presence of humic substances. When plants need nutrients, they release organic acids that dissolve soil minerals to feed both themselves and soil microbes. In other words, when plants are deficient in nutrients, they release root exudates that feed soil microorganisms that in turn feed the plants. The bacteria that live near the plant root-soil interphase, called the rhizosphere, provide additional energy in the form of plant growth promoting substances, and even antibiotics to ward off diseases,²⁶ something that synthetic chemicals can't do, and often do just the opposite by triggering plant disease susceptibility.

Surface Chemistry

A very critical condition that drives biological activity is *surface chemistry*. Because reliance on water solubility is counter intuitive, other factors become extremely important, such as surface structure. Surfaces must be recognized by microbes and compatible with enzymes,²⁷ allowing relatively small amounts of energy to convert minerals into plant food. It's analogous to your recognizing a fried hamburger as food and a cow pie as excrement. Both are about the same color and made of carbon compounds, but you instinctively know what to do with each one.

The surfaces of natural minerals are recognized by microbes as compatible surfaces for the conversion of the minerals into plant nutrients. Soluble synthetic fertilizers have extremely high levels of electrostatic charge on their surfaces (otherwise they would not be soluble in water), whereas living systems bring nutrients in through their membranes by first recognizing a compatible material and then providing a number of mechanisms to convert the minerals into nutrients. It is an extremely efficient low energy process that uses biological work provided by enzymes supplied by many soil organisms.

Low surface charge is critical to hydrophobic conditions for microbes. Therefore, low salt conditions, organic matter and carbon dioxide buffering must be maintained for thermodynamically favorable adsorption of bioactive organic substances and bacterial adhesion to surfaces.²⁷

Chiral Chemistry

One thing nature does consistently, and chemists can only come close to duplicating, is the phenomena of chirality; one of the hallmarks of the biomolecular building blocks of life on Earth.²⁸ Simply put, it is similar to the way your left hand is different from your right: essentially one is a mirror image of the other but you can't interchange gloves that are made for them. The word chiral is derived from the Greek language meaning hand. Just as your hands are identical in every way except how they are configured, chemicals of identical formulas can be put together in more than one way, thus changing their structure, and their chemistry.

Figure 5. Chiral chemicals

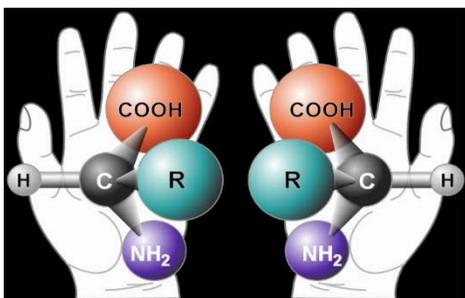


Figure 5 is an example of mirror images of chemicals compared to the similar mirror image of your hands. Both chemicals in the drawing have the same chemical formula, but they are completely different chemicals. Synthetic fertilizer inputs are a mixture of chemical forms that may not be recognized by microbes as something they can readily utilize, therefore they are ignored by microorganisms.

The same chiral principle can be applied to some natural mined inputs. Although limestone rock has the same chemical formula (CaCO_3) of biologically mineralized calcium carbonate (biogenic calcite), the rock does not have the chiral surface that is recognized by microbes, nor does it adsorb amino acids. Biogenic calcite presents a crystalline surface that is shaped in such a way that it will adsorb *l*-amino acids, the only form of biologically active amino acids, and other biologically active forms of organic molecules, due to the presence of chiral surfaces. Those same chiral surfaces aid in the adhesion and biological action of microbes that adhere to the calcite surface to break it down; that does not happen on limestone surfaces, otherwise the limestone used 1936 years ago to build the Coliseum in Rome would have been broken down by microbiological activity a long time ago.

Lessons from Drug Development: Anyone can dose

In recent years, drug developers have been approaching drug delivery in a systematic approach to overcome barriers to the *bioavailability* of drugs. Just like highly soluble fertilizers applied to soils, highly soluble drugs must be “dosed” in greater and greater quantities to achieve effectiveness because they are not transported across cell membranes efficiently due to chemical instability. Just as applying highly soluble chemical fertilizers to soils, the inefficient over-dosing of soluble drugs results in the excretion of those drugs via the urine and feces of livestock and humans causing a new form of environmental pollution.²⁹

Drug developers realize that taking advantage of the hydrophobic effect is the key to increasing the bioavailability of drugs. The chiral design of a drug can take advantage of how materials are efficiently transported across the cell membranes. When a target molecule lands on a cell membrane, it triggers important chemical cascades that allow the material to attach and then transported through the membrane. The attachment and transport are under hydrophobic and lipophilic (fat loving) conditions, where water is mostly excluded. The same thing happens with microbial activity in the rhizosphere of plant roots.

Balance

Mother Nature, of course, has figured out what substances are compatible with cell membranes, and what systems are energetically efficient for life, so it behooves researchers to apply the knowledge of biochemistry, surface chemistry, and thermodynamics to regenerative agriculture. Encouraging soil microbes to build organic matter (humus), adding humus in the form of compost, and combining humic substances (humates) with fertilizers can go a long way in providing the balanced conditions necessary for the life processes in soils. All of these practices support bioenergetics²⁵; the efficient use of the energy flowing through the soil system.

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