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Phosphorus Usage by Turfgrasses

The Energy Nutrient

Often Neglected by Turf Managers

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Of the three general fertilizer nutrients, nitrogen (N), phosphorus (P) and potassium (K), phosphorus is often the least understood and the most neglected. While the N and K content of grass leaves is about 3-4% of their dry weight, that of P is only one-tenth as much at 0.3-0.4% (Turner and Hummel 1992). This lower quantity in plant tissues and the fact that obvious P deficiencies are almost never observed in turf may contribute to its lesser standing among many turf managers. However, few nutrient elements play a more pivotal role in the metabolic processes of all living organisms including turfgrasses. In this article, the second in a series on turfgrass nutrients, I will outline some of those important functions performed by P and show how they

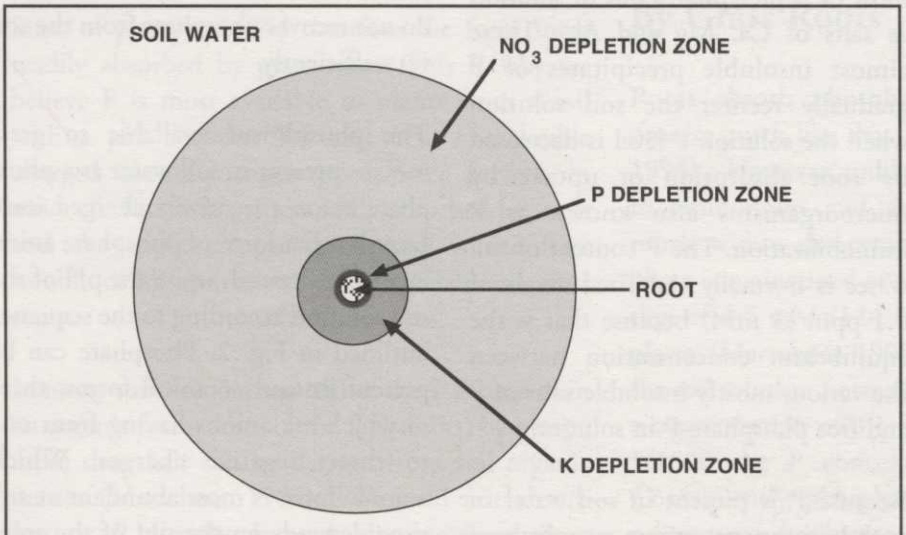

Fig. 1. Cross section of nutrient depletion zones around a grass root for phosphate, potassium and nitrate. Drawn to scale but enlarged five times.

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relate to turfgrass growth and quality. Finally, this information will also be interpreted in terms of turf management practices.

P Availability in the Soil

Of the six macronutrients (N, P, K, Ca, Mg & S) the concentration of P in the soil solution is by far the lowest. While N and K are present in the water of a typical soil at concentrations of 1-5 and 10-20 parts per million (ppm), respectively , P is normally present at a concentration of 0.05-0.15 ppm. The amount of P in solution at any given time is a very small percentage of the total P present in a soil. This is true because salts of P are often highly insoluble in water and such salts normally are formed when soluble phosphate fertilizers are added to a soil.

In acid soils, P is less available as a result of its association with iron (Fe), aluminum (Al) and manganese (Mn). In less acid or well limed soils, P is more abundant in soil water but still most of it precipitates out of solution as salts of Ca, Mg and Al. These almost insoluble precipitates of P gradually reenter the soil solution when the solution P level is decreased by root absorption or uptake by microorganisms also known as P immobilization. The P content of soil water is normally stabilized at about 0.1 ppm (3 mM) because that is the equilibrium concentration between the various mostly insoluble salts of P and free phosphate-P in solution.

Because P is present in soil water in such low concentrations, very little of it is transported with the flow of water through the soil profile. Consequently, P is relatively immobile in the soil. It does not leach readily even when large quantities of rain percolate through the soil. Phosphorus also does not move very much with soil water as it is absorbed by roots during rapid transpiration. This relative immobility of P means that roots are not very efficient in removing P from the soil. Most soil P does not come under the influence of an absorbing root even when the root system is fibrous and dense as it is under turf (Fig. 1.).

According to research reported by Stan Barber at Purdue University (1984), the zone of phosphate depletion from soil water around a living corn root is only 0.2 mm (0.0079 inches) while by comparison, the nitrate depletion zone is approximately 10 mm.(0.39 inches). That means a root can remove nitrate from about 450 times more soil than it can phosphate. This also means that, not only is P available to a plant root from a soil solution that has a very low phosphate concentration, but it can be absorbed by roots from only a very small portion of the total soil. It should come as no surprise that roots do not recover phosphate from the soil very efficiently.

The phosphorus available to grass roots is present in soil water as a phosphate anion (negatively charged ion). Exactly what form of phosphate anion is present depends upon the pH of the soil solution according to the sequence outlined in Fig. 2. Phosphate can be present in four chemical forms, three of which are anions having from one to three negative charges. Which anionic form is most abundant at any time depends on the pH of the solution. As an acid solution becomes more basic (the H+ ion concentration decreases and the OH- ions increase)

$$H_3PO_4 \overset{pKa = 2.1}{\longleftrightarrow} H_2PO_4^{-} \overset{pKa = 7.2}{\longleftrightarrow} HPO_4^{-2} \overset{pKa = 12.7}{\longleftrightarrow} PO_4^{-3}$$

PHOSPHORIC ACID — DIHYDROGEN PHOSPHATE ION — MONOHYDROGEN PHOSPHATE ION — PHOSPHATE ION

Figure 2. The acid and three ionic (charged) forms of phosphate found in soil solutions.

phosphoric acid (H3PO4) loses its H+ until eventually it becomes a triple charged phosphate anion (PO_4^{-3}).

The pKa values shown in the sequence (Fig. 2) are the pH values of a solution where the phosphate ions are equally divided between the two forms on either side of the double headed arrow. For example, when the solution pH is 7.2, half of the phosphate present will be in the $H_2PO_4^{-1}$ form and the other half will have one less H+ and be present as HPO_4^{-2}. Since many soils on which turf is grown have a pH of between 5.5 and 6.5, most phosphate in the solution of those soils will be present as the single charged dihydrogen phosphate ($H_2PO_4^{-1}$) anion. This is the most soluble form of phosphate and therefore the form most readily absorbed by grass roots. This is why we believe P is most available to plants from a soil with a pH between 5.5 and 6.5. The double charged monohydrogen phosphate, present in more alkaline soils, is less easily absorbed by roots and the triple charged phosphate is the least soluble of all and essentially unavailable to grass roots.

In many soils, more than half of the P is present in an organic form. Also, of the P absorbed by plants, more than half can be derived from soil organic matter (Marschner 1995). Plants do not absorb organic P directly. Instead, the roots excrete a phosphatase enzyme (mostly at the tip regions) and it hydrolyses the organic P releasing it as inorganic phosphate. This liberated phosphate can be absorbed by roots as described below. The release of phosphatase is often a response by roots to a P deficiency condition. Thus, if soil inorganic phosphate does not meet plant needs, the roots will secrete an enzyme which degrades organic P making phosphate available for absorption. In addition, soil microorganisms also secrete phosphatases and can make organic P available to plants. For this reason, P deficiency is rarely observed in a soil rich in organic matter that supports a large population of microorganisms. This also may explain why P deficiencies are rarely observed in established turf.

Phosphate Absorption By Grass Roots

Roots absorb phosphate by an active uptake process much like that described for nitrate (Hull 1994). However, unlike nitrate which is reduced to ammonium and does not accumulate very much within the cytoplasm of root cells, phosphate is maintained at a relatively high concentration of 4-5 mM (124-155 ppm) within the cytoplasm (Marschner 1995). As mentioned earlier, the soil solution normally contains phosphate-P at a concentration of 0.1 ppm (0.003 mM) which is 1/1500 the P concentration inside root cells. Consequently, phosphate in the soil solution will never move freely into a root cell against such a steep concentration gradient. Because P does enter root cells and is concentrated there to a remarkable degree, energy must be expended in phosphate uptake. The story of how this comes about answers two important questions concerning P nutrition in turf: (1) how it is absorbed from a dilute soil solution and (2) how it is used to transform chemical energy into mechanical energy.

Because phosphate cannot enter a root cell passively, its uptake must be driven by an energy source acting inside the cell. This energy source is the P containing chemical adenosine triphosphate (ATP). The three linked phosphates of ATP (Fig. 3) are joined by highly reactive chemical bonds which when broken liberate substantial amounts of energy. ATP is hydrolyzed to ADP and $H_2PO_4^-$ and the energy liberated by that reaction can be used to drive the uptake of an anion across the plasma membrane of root cells (Fig. 4).

Two reactions are involved in this process. First, ATP is degraded to ADP (adenosine diphosphate) and $H_2PO_4^-$ by an enzyme present in the outer cell membrane.

ATP + H_2O ----------------> ADP + $H_2PO_4^-$

At the same time, this enzyme pumps a H^+ out of the cell into the external solution. As this enzyme continues to consume ATP and transport H+s from the cytoplasm into the soil solution, the root cell walls and the soil become increasingly acid and the cytoplasm becomes alkaline. Remember, for every H^+ pumped out of the cell a OH^- is left behind and that makes the cytoplasm alkaline. Because each OH^- containes a negative charge, the cytoplasm also becomes negative compared to the outside solution which accumulates H^+ and becomes positive.

Thus, the consumption of ATP creates two gradients across the cell's outer membrane: a pH gradient (DpH) and an electrical gradient (DE) based on charge differences across the membrane. These gradients represent a source of energy which was derived from the chemical energy liberated when ATP was hydrolyzed to ADP and $H_2PO_4^-$. This gradient energy can now be used to transport anions into the cell against a concentration gradient. Fig. 4 shows $H_2PO_4^-$ being transported across the membrane along with a H^+. This works because the transport of H^+ into the cell is favored. A H^+ has a positive charge so it will move from a region that is positive (the cell wall and soil solution) into one that is more negative (cytoplasm of root cells). Also, the H^+ concentration outside the

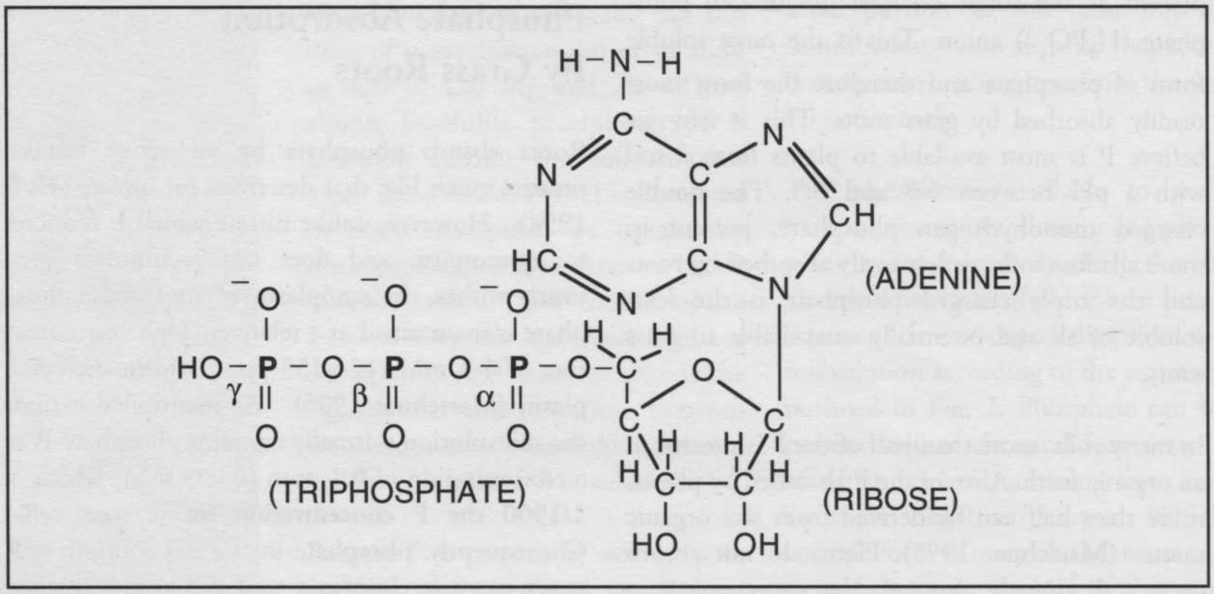

Figure 3. Chemical structure of Adenosine TriPhosphate (ATP) showing the three high energy phosphates.

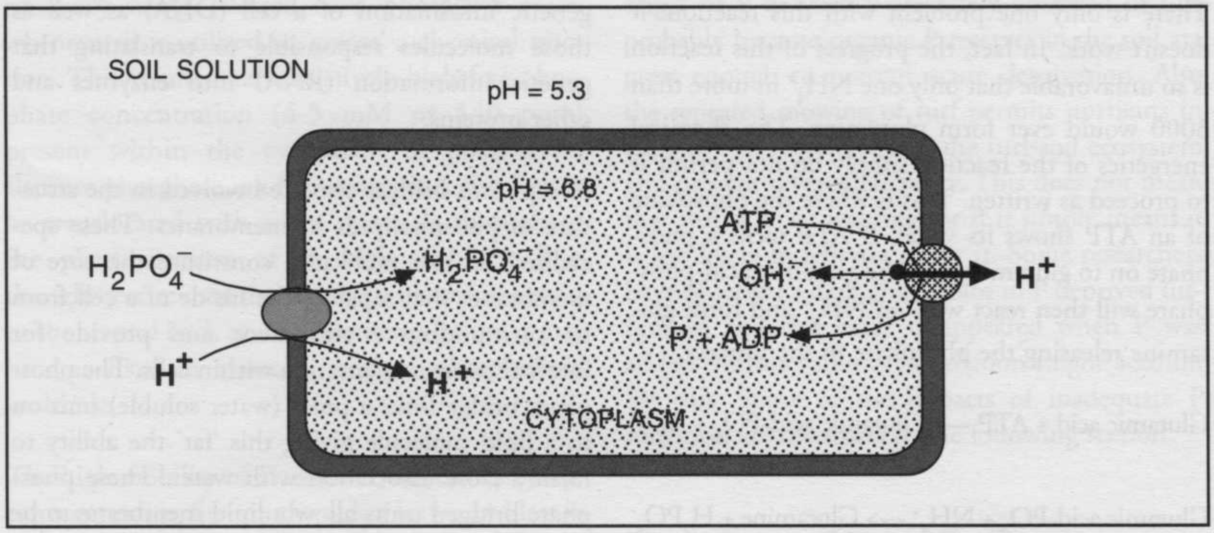

Figure 4. Energetics of phosphate uptake by plant cells. The H+ gradient across the cell membrane created by the hydrolysis of ATP is used to power the uptake and accumulation of P.

cell is much greater than it is inside. Because of these two gradients, H^+ will move spontaneously from the soil solution into the cell.

However, membranes are impermeable to H^+s and they can only cross them if a protein carrier is present. Such a protein is present, but it will only allow H^+s to cross if they carry an anion (in this case $H_2PO_4^-$) at the same time. These protein carriers are called cotransporters. They effectively harness the energy driving H^+s into the cell in order to move $H_2PO_4^-$) in as well, even though the uptake of phosphate might not occur on its own. So long as the energy gradients driving H+ into the cell are stronger than any gradients keeping phosphate out, phosphate will cross the outer cell membrane and enter via the cotransporter.

This is how phosphate enters a root cell even though the inside concentration is substantially greater than the outside concentration. It also shows how the chemical energy contained in the phosphate bonds of ATP can be used to do mechanical work, pump H+ out of a cell which in turn provides the energy for the uptake of more phosphate or other anions into the cell. This use of phosphate bond energy to power other reactions constitutes the major role of P in plant metabolism; animal metabolism too.

Metabolic roles of P

Anion uptake by cells is only one example of how phosphate bond energy is used to do the cell's work. There are numerous other cases where phosphate bonds permits metabolic reactions to proceed when otherwise they would not, or would do so very slowly. An example of this critical role played by P is the reaction through which ammonium-N (NH_4^+) is incorporated into amino acids (the building blocks of proteins). The reaction by which this occurs is as follows:

Glutamic acid + NH_4^+ --------> Glutamine + H_2O

Here an NH_4+ is bonded to a carbon atom of glutamic acid (an amino acid) forming glutamine which in turn can pass that N on to other organic chemicals making many N-containing compounds essential for plant growth. This is the chemical mechanism by which most inorganic nitrogen is incorporated into organic matter in both plants and animals.

There is only one problem with this reaction: it doesn't work. In fact, the progress of this reaction is so unfavorable that only one NH_4^+ in more than 3000 would ever form glutamine. The chemical energetics of the reaction simply do not permit it to proceed as written. This is where the phosphate of an ATP shows its value. If ATP tacks a phosphate on to glutamic acid, the glutamic acid-phosphate will then react with an NH_4^+ and form glutamine releasing the phosphate in the process.

Glutamic acid + ATP ---> Glutamic acid-PO_4 + ADP

Glutamic acid-PO_4 + NH_4^+ ---> Glutamine + $H_2PO_4^-$

The energy present in the phosphate bonds of ATP allows it to react with glutamic acid to form a phosphorylated glutamic acid. This phosphorylated glutamic acid now contains enough energy that it can react with NH_4^+ and form glutamine. Through the involvement of ATP, these two paired reactions are so favored that only one NH_4^+ in 700 will fail to become part of a glutamine. In other words, the energy present in an ATP was used to allow an unfavorable reaction to become highly favored.

The phosphate transfered to an organic molecule by ATP serves as the grease which overcomes energy barriers during most biosynthetic processes including photosynthesis and the production of proteins, fats, complex carbohydrates and nucleic. In other words, the stuff of life depends on the energy transmitted through phosphate bonds. This is why P is known as the energy nutrient.

Phosphorus in Macromolecular Structure

Phosphorus also serves a structural function in plant chemistry. In nucleic acids, P forms a bridge between adjacent ribonucleotide units of DNA and RNA giving them their primary level of organization, the nucleotide sequence, the genetic code. Thus, P maintains the structure of those macromolecules responsible for carrying the genetic information of a cell (DNA) as well as those molecules responsible to translating that genetic information (RNA) into enzymes and other proteins.

Phosphorus bridges also are involved in the structure of phospholipids in membranes. These specialized fat-like molecules constitute the core of membranes that separate the inside of a cell from its surrounding environment and provide for internal compartmentation within cells. The phosphate bridge links a polar (water soluble) unit on to a lipid molecule giving this 'fat' the ability to form a close association with water. These phosphate bridged units allow a lipid membrane to be wet and permit water soluble nutrients and organic molecules to approach the membrane and possibly to be transported across it.

It is evident that P plays a central role not only in plant metabolism but in maintaining cellular structure. Recent evidence shows that P can also function to regulate the activity of enzymes. The function of these catalytic proteins was discussed in the first article of this series on nitrogen (Hull 1996). There we discussed that the activity of an enzyme was very much controlled by its structure: its ability to bind chemical reactants in the appropriate way so they can form bonds with each other. Now we know that an enzyme's structure can be changed by becoming phosphorylated through the action of ATP. Apparently the formation of phosphate esters and their later destruction is a major mechanism by which a cell can control the activity of many enzymes.

P Circulation in Plants

Phosphorus is among the most mobile nutrient elements in plants. It can be absorbed by roots and transported via the xylem to the stems and leaves. Once in the leaves, phosphate can enter the sieve elements of the phloem and be translocated to wherever the demand for energy (sugars made by photosynthesis) carries it. Thus, P is effectively transported to growing points of the plant where the need for it is greatest. This high degree of mobility is probably due to the fact that P is continuously being released as a phosphate anion whenever it is utilized to 'grease' a chemical reaction. This results in the relatively high free phosphate concentration (4-5 mM or 140 ppm) present within the cytoplasm of plant cells. Because phosphate is a free anion, it is also free to be translocated with other materials throughout the plant. Because of its high mobility, P is thought to circulate throughout a plant from roots to shoots and back again many times before it may become fixed in a nucleic acid or phospholipid molecule.

The high mobility of P results in deficiency symptoms appearing first on the oldest leaves and last in new growth. This mobility also increases the efficiency of P use so that deficiency does not become apparent until P drops to very low levels. When P becomes limiting, the first symptom is a reduced growth rate. This is rarely evident in the field unless a P sufficient plants is nearby for comparison. Low P will stimulate root growth at the expense of shoot growth, interestingly opposite from the effects of high N rates (Hull 1996). This is a favorable response because it increases the plant's ability to find more P by allowing it to explore a larger soil volume. As P becomes limiting, the synthesis of macromolecules (polysaccharides, nucleic acids, proteins) is inhibited first because the synthesis of these chemicals has a high requirement for ATP. Photosynthesis is less affected by low P so simple sugars accumulate but, since their use for growth is inhibited, they are translocated to roots where they stimulate their growth. Any P obtained from the soil enters via the roots and can be used there first to support continued root growth. That is how low P favors growth of roots more than shoots.

The accumulation of simple sugars also stimulates the synthesis of some pigment molecules especially anthocyanins. These give leaves and stems a dark purple coloration which constitutes the most obvious symptom of P deficiency. It is important to remember that anthocyanin synthesis is among the last events during P deprivation. Consequently, much growth reduction and metabolic disturbance has already occurred before purple coloration can be observed. These advanced stages of P deficiency are rarely observed in turf probably because organic P reserves in the soil are great enough to prevent acute deprivation. Also the repeated mowing of turf permits nutrients in clippings to recycle within the turf-soil ecosystem and prevent severe deficiency. This does not mean that turf is never wanting for P, it simply means it is less likely to tell you about it. Some researchers have observed a dark green color in P deprived turfgrasses and this color disappeared when P was added. Anthocyanin accumulation might account for this. Some of the impacts of inadequate P nutrition are discussed in the following section.

Functions of P in Turf

Possibly because of concerns over P contamination of surface water due to runoff or because turf fails to respond dramatically to P fertilization, most turf fertilizers are low in P and some turf managers avoid it altogether (Christians 1993). However, P is absolutely essential for plant growth as we have shown and the turf manager who does not recognize this does so at some considerable risk. The remainder of this article will consider those functions of P in turf culture that have been documented in the scientific literature. For a more comprehensive discussion, I refer you to the excellent review prepared by Turner and Hummel for the latest Turfgrass Monograph published by the American Society of Agronomy (1992).

a. *Recovery From Stress*: Turf is subjected to a number of stresses during a normal growing season. Climatic, biotic and use factors all contribute to stress from time to time and a well managed turf is one that sustains little injury from such stresses or when injured recovers rapidly and completely. There are several reports of warm-season turfgrasses exhibiting greater cold tolerance when supplied with recommended levels of P. Similar results have been observed in cool-season grasses but there a P response depends on N and K also being at appropriate levels. Kentucky bluegrass turf recovered more quickly from summer drought if P was not limiting especially when N levels were high (Schmidt and Breuninger 1981). Phosphorus sufficiency also has been observed to increase the efficiency of water use under drought conditions. This may be a result of greater root growth frequently attributed to proper P nutrition.

It is clear that proper nutrition increases the ability of turf to tolerate and recover from stress. However, no nutrient functions alone and can exhibit its positive effects only when other nutrients are adequately supplied. Thus, the positive impact of P may not always be apparent if N, K or some other nutrient is either limiting or present in excess. The secret to proper turf fertilization is a balanced offering of nutrients, not allowing any one to become excessive or inadequate.

b. *Reducing Disease Infection*: There are numerous reports of turf disease being suppressed by applications of P. Stripe smut, take-all patch, brown patch and red thread all have been reported to be less damaging to turf when P supplies were adequate (Turner and Hummel 1992). However, for every report of a positive response to P, there is another reporting no disease suppression resulting from P additions.

Again, the issue of nutritional balance plays an important role in how turf responds to the addition of a single nutrient. This was evident in a Rhode Island study (Hull et al. 1979) of 'Merion' Kentucky bluegrass turf infected with stripe smut (Table 1). This turf had been maintained at four nutrient ratios for eight years and three fertility rates for five years before it became heavily infected with stripe smut. It is evident that turf fertilized with all three fertilizer nutrients, which prevented a nutritional imbalance, was less seriously infected by the fungus. It is equally evident that heavily fertilized turf was more susceptible to stripe smut than that fertilized at a low rate. The heavily fertilized turf may have become nutritionally imbalanced with respect to other nutrients (Ca, Mg, S, Fe) not considered in this experiment. Clearly the addition of P or K in addition to N reduced the incidence of disease but the addition of P plus K had more than an additive effect on further reducing infection. Turf diseases are opportunistic and take advantage of turf whenever its defenses are weakened and conditions for disease are favorable (Nelson 1994).

The role of P in promoting disease resistance is not difficult to understand. Whenever a plant is challenged by a stress, especially a pathogen or insect, the plant responds by altering its metabolism to produce defensive chemicals. Several phenol-based compounds are synthesized in response to a pathogen assault and these are inhibitory to the growth of the fungus. This is a complex process and the timing of the plant response is important if an effective defense is to be mounted. Any sudden change in metabolism requires the induction and activation enzymes as well as a massive shift in the flow of photosynthetic products along different biochemical pathways. All these processes require the formation of phosphate bonds along with the synthesis and utilization of much ATP. Thus, if P is in short supply or badly out of balance with other nutrients (especially N) these processes will not occur or will be delayed and the disease will be given an opportunity to become established.

c. *Turf Establishment*: Seedling responses to P are among the most critical and dramatic in the annals of turfgrass fertility (Turner and Hummel 1992). Numerous reports have been published on the positive responses of cool-season turfgrass seedings to additions of P. A similar but somewhat less dramatic P response has been observed during vegetative establishment of warm-season turfgrasses. Plant vigor, stand density and percent cover all increase when P is applied at time of seeding. Increases in stand density due to P additions have been observed 3-4 weeks after germination and persisted for 8-10 weeks. Phosphorus additions to a seedbed are also reported to stimulate spring green-up and increase clipping yields for 6-9 years following establishment.

These dramatic turfgrass responses during establishment could be demonstrated only when soil P levels were moderate to low (less than 150 lbs. available P per acre). When soil P levels were high, additional seedbed applications had little impact on establishment, indicating that P availability during the first few weeks is critical for grass seedling growth. The most critical tasks facing a grass seedling are to make root contact with soil water and to display a green leaf to sunlight.

Table 1. Stripe smut infection of 'Merion' Kentucky bluegrass fertilized at 4 nutrient combinations for 8 years.†

Nutrients Applied	*Fertilizer rates (lbs/1000 sq-ft/year N-P-K)* 2.4-0.4-0.8	4.8-0.8-1.6	9.6-1.6-3.2	*Average*
	% smutted tillers			
N:O:O	7.6 de*	13.1 e	40.3 g	18.5 s
N:P:O	1.4 ab	4.8 bcd	29.6 f	9.0 rs
N:O:K	1.2 a	5.7 cd	25.5 f	8.4 rs
N:P:K	2.1 abc	1.7 ab	11.4 e	4.1 r
Average	2.6 x	5.7 y	25.9 z	

* All values followed by the same letter are not significantly different
† Modified from Hull et al. 1997

Because the P concentration in soil water is so low, a seedling must penetrate a reasonable volume of soil before its reserves of seed P become exhausted. Placing fertilizer P in the seedbed insures that P sufficiency will be established quickly. Early demands for P are high because the number of rapidly growing and dividing cells (meristems), as a percent of the total number of cells, is greatest during establishment. Rapidly growing tissues have a greater requirement for P than more mature tissues because of the larger number of P-dependent biosynthetic reactions taking place. Because mature tissues often contain reserve P in the large central vacuoles of their cells, vegetative establishment of warm-season grasses and sod establishment of all grasses normally does not respond as positively to seedbed P additions. Remember, P is highly mobile in plants and can move easily from older mature to younger growing tissues.

d. *The Poa Annua Situation*: Phosphorus fertilization of bentgrass greens has been reported to result in an invasion of *Poa annua* (Waddington et al. 1978). *Poa annua* has poor tolerance for heat and drought stress but when available P levels are in excess of 200 lbs/acre, *Poa annua* is less injured by these stresses and becomes more invasive of other cool-season turfgrasses. Consequently, when *Poa annua* is the principal grass on greens or other fine turf areas, it is managed for maximum survival and that normally includes maintaining relatively high levels of available P. Because of this link between P fertilization and *Poa annua* persistence, many turf managers reduce or even eliminate the use of P on greens and tees when *Poa annua* invasion is being suppressed. This may be a risky practice because bentgrasses also have a requirement for P, it just might be less than that for *Poa annua.*

This role of P in *Poa annua* aggressiveness has been questioned by Wayne Kussow at the University of Wisconsin (1992). He was unable to demonstrate a connection between P availability and *Poa annua* invasion of creeping bentgrass turf. He also cited several investigators who found that *Poa annua* responded more dramatically to added N than P and concludes that *Poa annua* offers greater root competition to bentgrasses when N levels are high. Several experiments were described which suggest that *Poa annua* invasion of bentgrass greens and tees is related to the density of the turf and the amount of exposed soil available for *Poa annua* seed to germinate and become established. Worm casts offer just such opportunities for *Poa annua* establishment and their frequency was greater in N sufficient turf. However, when N levels were very high, turf density was so great that *Poa annua* seedlings could not become established and their invasiveness was reduced. Also, low N turf was not successfully invaded by *Poa annua* and this was interpreted as showing that bentgrass roots were more competitive under low nitrogen fertility. In these experiments, P was not studied so it is not certain that the reduced invasiveness of *Poa annua* under low N might not also hold for low P. As mentioned earlier, an interaction among nutrients is the rule rather than the exception. The question of whether bentgrasses are more competitive than *Poa annua* under low P or N fertility will not be answered until the nutrient uptake capabilities of each grass are measured under controlled conditions which mimic a field situation.

Genetic differences in P requirements among turfgrasses have been reported. Turner and Waddington (1983) found that the establishment of Chewings fescue required less P than either Kentucky bluegrass or perennial ryegrass. Liu et al. (1995) studied the characteristics of P uptake by ten cultivars each of three turfgrasses and found that tall fescue roots had a greater affinity for P absorption than perennial ryegrass or Kentucky bluegrass. The capacity for P uptake (maximum rate of uptake) did not differ among these three grasses, but daily P recovery in clippings was greatest for tall fescue while its P concentration in leaf tissue was lowest (Table 2). This indicates that the efficiency by which grasses absorb, utilize and probably recycle P during a growing season varies among grass species and appears to be genetically controlled.

If turfgrasses do differ in their ability to recover P from the soil and utilize it for energy metabolism, such differences may explain changes in grass competitiveness under different levels of P nutrition. *Poa annua* may be less competitive against bentgrasses when P availability is low but becomes more competitive when P is less limiting. In the future, cultivars of several turfgrass species may be developed that are more efficient in P recovery and use and because of this will be more competitive against invading weeds or other grasses. This may prove to be an effective strategy for reducing weed competition in turf without relying on herbicides and at the same time reducing the need for P fertilizers.

e. *Phosphorus Toxicity*: We sometimes are cautioned about the potential for P toxicity as a justification for formulating turf fertilizers with little or no P. Because of the high capacity of most soils to fix P chemically, its concentration in the soil solution rarely becomes high enough for grasses to absorb toxic levels. In solution culture, when P is added after a period of P deprivation, absorption may be very rapid for several hours. Even then, speedy P transport to shoots reduces the risk of toxic concentrations occurring in roots and dilution within stems and leaves minimizes toxicity there. Within plant cells, cytoplasmic P levels are held within fairly tight limits by transporting any excess into the large central vacuole. There it serves to stabilize the concentration of P in the cytoplasm at near optimum levels. This control over cytoplasmic P also tends to minimize the potential for toxicity.

Table 2. Comparative P recovery in clippings of three turfgrasses grown under field conditions (Average of 10 cultivars per grass species during 2 growing seasons).†

Turfgrass	*Clipping growth rate*	*Clipping P concentration*	*Daily P recovery*
	g/m²/day	*mg/g dry wt.*	*mg/m²/day*
Tall fescue	3.0 a*	3.7 c	11.0 a
Kentucky bluegrass	2.5 b	3.9 b	9.1 b
Perennial ryegrass	2.0 c	4.7 a	9.5 ab

* Values in a column followed by the same letter are not significantly different.

† Derived from Liu et al. 1995.

Phosphorus Management of Turf

Based on the principles outlined in the accompanying article, some general suggestions governing P management in turf can be made.

1. Phosphorus applications should be made to a mature turf based on the results of soil tests for plant-available P and/or tissue analyses. Because most soils contain so much P that is not available to plant roots, it is important to know how much readily available and slowly available P is present in a soil at the beginning of a growing season. For most soils, 150 to 200 lbs. of available P per acre should easily satisfy turf needs.

2. Incorporate P fertilizers throughout the soil profile before seeding or sodding turf. Phosphorus is so immobile in soil that its penetration throughout the root zone from surface applications will occur very slowly if at all.

3. Apply P fertilizer in the fall. In most parts of the US, rainfall is more abundant during the fall-winter-spring season than it is during the summer. Phosphorus is incorporated into the soil under an established turf mostly by water infiltration, possibly assisted by freeze-thaw cycles, so P application prior to the wet cold season will enhance soil incorporation. Do not apply P, or any fertilizer, on snow or frozen ground. That practice may promote excessive runoff and contaminate surface water bodies.

4. Maintain a balanced fertilizer program. Plants require six macronutrient elements and all should be considered when culturing plants especially on a non-soil medium. While P deficiency is not common on turf, its requirement for healthy grass is as great as that of any macronutrient. The ratio of nutrients in fertilizer should approximate the ratio in plant tissues. A radical departure from such a ratio can cause metabolic disorders due to nutrient imbalance which may promote intolerance to stresses, greater disease susceptibility and generally poor growth.

5. If clippings are retained, P applications to an established turf may be reduced. There is virtually no P loss from a turf-soil ecosystem if clippings are not removed. In such a case, consistent with 4 above, P may accumulate in the soil and further additions may serve no purpose. Again, this will be a valid consideration only in established turf where clippings have not been removed for many years.

6. Monitor soil pH and apply lime as needed since P availability to roots is directly influenced by the H+ concentration of the soil solution. Lime applications can easily be overlooked by turf managers and the soil pH can drop below the optimum for most turfgrasses. This will have several negative effects on turf growth not the least of which may be reduced P availability and fluctuating incipient P deficiency.

7. If a low pH or P availability problem are detected and turf re-establishment is not an option, apply lime and P fertilizer in conjunction with aerification treatments. By allowing these materials to infiltrate into aerification holes, their incorporation into the soil profile can be achieved without disrupting the turf. While this method is not very efficient, with time, it can correct soil pH or fertility problems more quickly than surface applications.

8. Do not rely on deficiency symptoms to indicate when P must be applied since symptoms are rarely seen on turf. An appropriate soil analysis is the best way to monitor P availability. Tissue analysis is less reliable since the P content of turfgrass leaves can vary greatly depending on the rate of leaf growth and the health of the root system. The best approach to maintaining proper P nutrition of turf is to make an annual application approximately equal to the P removed or fixed within the soil (about 4-8 lbs P/acre/year).

In short, concerns over P toxicity in turf probably are exaggerated. The only situation where I can imagine P toxicity occurring would be on a sand green which had been maintained at very low P levels but was suddenly given a heavy P application. The sand substrate would be less able than a soil to immobilize fertilizer P, root absorption would be rapid and the shoots, being mowed so closely, would have limited capacity to dilute P translocated from the roots to shoots. Excessive cytoplasmic P would still be of short duration as transport into vacuoles could remove most of it. Injury caused by phosphate precipitating basic cationic nutrients (Mg^{+2}, Fe^{+3}, Zn^{+2}, Cu^{+2}) or disrupting biochemical pathways involving phosphorylated intermediates (photosynthetic carbon fixation) might occur but would not be long lasting.

Phosphorus can accumulate in the soil and if clippings are not removed there are few avenues by which it will be lost from the turf-soil environment. Consequently, annual applications of P to mature turf that has been in place for several years is probably unnecessary. While P toxicity is unlikely to be a problem, additional applications will do no good and are a waste of money. Like all additions made to turf, applications of P should be based on soil or tissue analyses and a sound understanding of plant needs.

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Terms to Know

Anion - A negatively charged chemical entity. Anions can be inorganic (H_2PO_4-, NO_3-, SO_4-2) or organic (acetate, glutamate). In solutions, their concentration is normally balanced by an equivalent number of positively charged cations.

Cytoplasm - The portion of a plant cell's interior located between the cell wall and the central vacuole.

Hydrolysis - A chemical reaction by which a chemical bond is broken with the addition of w water molecule. ATP + H_2O) ---> ADP + H_2PO_4- is a hydrolytic reaction.

Monohydrogen or **dihydrogen phosphate** - The forms of phosphate anion that contain one or two hydrogens. Also known as dibasic or monobasic phosphate in recognition of the number of basic cations each can bind.

Vacuole - A membrane bounded cavity in the center of most plant cells filled with water, in addition to salts, enzymes, waste products and, in some plants, storage carbohydrates. Vacuoles frequently constitute most of the volume in mature cells and can serve to stabilize the cytoplasmic concentration of nutrient ions and salts.