SOIL NUTRIENT MANAGEMENT FOR FORAGES

PHOSPHORUS, POTASSIUM, SULFUR AND MICRONUTRIENTS

Kathrin Olson-Rutz Research Associate
Clain Jones Extension Soil Fertility Specialist

Department of Land Resources and Environmental Sciences, Montana State University, Bozeman

MONTANA STATE UNIVERSITY EXTENSION

new 2014 EB0217

INTRODUCTION

Improvements in forage production have the potential to increase income and significantly reduce livestock production costs. Rotating forages with annual grain crops can increase grain yields, reduce weeds, improve soil quality, and reduce system energy requirements *(1)*. Soil fertility is important for forage production, stand health/longevity, and forage quality.

An important step towards soil fertility is nurturing soil health. In forage production this includes: allowing adequate plant recovery time, encouraging plant species diversity, and leaving cover and standing material to buffer changes in soil temperature and help store water. These may increase soil organic matter, aggregation, and water and nutrient availability, and may improve plant resistance to stresses and increase yields. Contact the National Resources Conservation Service (NRCS) for more information on management for soil health.

This bulletin focuses on phosphorus (P), potassium (K), sulfur (S) and micronutrients for established perennial forage stands. Nutrient management for stand establishment and annual forage crops is slightly different than for established stands and will be discussed briefly. Nitrogen (N) management is presented in EB0216. Nutrient management for annual legumes is similar whether produced for grain or forage and is presented in EB0210. For additional information on plant nutrition, soil fertility, and specific nutrients see the Nutrient Management Modules. For information on species composition and grazing management, see EB0019 and EB0099. These, and other resources mentioned in this bulletin are listed under "For more information" at the end of this bulletin.

TABLE 1. Conditions that limit P, K, S and micronutrient availability, their mobility in soil, and common causes of available nutrient loss from production systems in addition to harvest.

Nutrient	Limiting conditions	Mobility in soil	Causes of nutrient loss
Phosphorus (P)	Cold, dry, weathered, sandy, high calcium soils pH < 6 or pH > 7.5	Immobile	Erosion, binding with calcium, aluminum, or iron
Potassium (K)	Cool, dry, saturated, sandy, high calcium, magnesium, or N, low soil organic matter soils	Relatively immobile	Binding between clay layers
Sulfur (S)	Cold, coarse, acidic, low soil organic matter, eroded soils	Mobile	Leaching, binding to calcium
Chloride (Cl) and Boron (B)	Cool, wet, < 2% soil organic matter, coarse textured soils pH < 7 or > 8.5 (B)	Mobile	Leaching
Micro metals: copper (Cu), iron (Fe) manganese (Mn) and zinc (Zn)	Cool, wet, < 2% soil organic matter, coarse textured soils pH > 7	Immobile	Bind strongly to soil or form minerals

MONTANA STATE UNIVERSITY EXTENSION

cover photo by Ann Ronning

NUTRIENT MANAGEMENT

Of the 17 nutrients that are essential for plant growth, P, K, and S are the main nutrients other than N that need to be added beyond what is available from the soil. The conditions under which P, K, S and micronutrients may be deficient are presented in Table 1.

The key to fertilizing for optimal forage yield and quality is to select the right fertilizer source, rate, placement, and timing for your operation (4R Concept). These are usually interrelated; for example, the right rate, placement, and timing are very dependent on the source. Nutrient mobility in the soil and common nutrient losses from the system (Table 1) influence fertilizer rate, placement and timing decisions. Getting it 'right' not only increases your bottom line, but helps protect our soil, water, and air resources as well.

NEW AND INTERSEEDING

Adequate amounts of P, K and S are necessary for healthy root growth, withstanding drought and winter stress, high quality forage, and N fixation in legumes. Soil testing helps fine-tune nutrients needed for early growth and identify possible limitations (e.g. acidity or salinity) for establishment (see MT200702AG). Because P and K are relatively immobile, they should be placed in the root zone. If soil P and K are below critical levels, build up soil P and K levels prior to planting by incorporating broadcast fertilizer. Apply 3-4 times the rate recommended based on soil tests (Tables 2 and 3) to supply 3-4 years of the plant requirement. If soil P is low, 10 lb P_2O_5/acre at the time of seeding can significantly increase seedling establishment. Due to the risk of seedling damage, no more than 20 lb P_2O_5/acre as monoammonium phosphate (MAP, 11-52-0), 26 lb P_2O_5/acre as triple super phosphate (TSP, 0-46-0), or 10-15 lb N plus K_2O/acre should be placed in the seed band. Higher rates may be banded one inch below and to the side of the seed. Diammonium phosphate (DAP, 18-46-0) is more toxic to seedlings than MAP and should not be seed-placed.

Basing rates on soil tests is particularly important with K. Although K is abundant in most Montana soils, the majority of soil K is unavailable to plants. Low K levels can reduce N fixation in legumes and cause a legume-grass field to quickly convert to mostly grass. High soil K levels can lead to high K concentration in forage which increases the risk of milk fever and can waste K fertilizer.

ESTABLISHED STANDS

Improving and maintaining forage stands with fertilizer is more effective at improving yields and quality than mechanical methods (aeration, harrowing and light disking) or interseeding, and generally less expensive than reseeding. However, fertilizing stands that have more undesirable than desirable species may increase production of the undesirable species. Weed control measures should be implemented near time of fertilization to maximize the return on fertilizer investment.

Source Not all fertilizer sources provide nutrients in plant available forms. Nutrient sources that need to be decomposed or broken down in the soil to become plant available (e.g. rock phosphate, elemental sulfur, or manure) will have a lag effect before the forage responds. They may provide nutrients too late to promote early spring growth, but can extend benefits for season-long forage or a late cutting.

Be aware that elemental S reduces soil pH which may inhibit legume N-fixation *(2)*. It should not be used in fields with, or intended for legumes if soil pH in the upper 6-12 inches is less than 6.5.

TABLE 2. Phosphorus fertilizer guidelines for alfalfa and grass in Montana based on soil analysis[1].

Crop	Olsen P Soil Test Level (ppm)				
	0	4	8	12	16[2]
	P Fertilizer Rate (lb P_2O_5/acre)				
Alfalfa	140	110	75	40	20[3]
Alfalfa/grass[4]	93	73	53	30	13
Grass	45	35	30	20	5

[1] From EB0161; [2] If soil test is above 16 ppm, then consider using up to removal rate (Table 4); [3] This was printed as 0 in EB0161, which is an apparent error; [4] Alfalfa/grass rates calculated for a 50/50 ratio.

TABLE 3. Potassium fertilizer guidelines for alfalfa and grass in Montana based on soil analysis[1].

Crop	K Soil Test Level (ppm)					
	0	50	100	150	200	250[2]
	K Fertilizer Rate (lb K_2O/acre)					
Alfalfa	240	205	170	140	95	30
Alfalfa/grass[3]	160	137	115	93	63	23
Grass	80	70	60	45	30	15

[1] From EB0161; [2] If soil test is above 250 ppm, then consider using up to removal rate (Table 4); [3] Alfalfa/grass rates calculated for a 50/50 ratio.

TABLE 4. Estimated pounds of nutrient removed per ton of alfalfa and grass harvested in Montana[1].

Crop	N	P_2O_5	K_2O	S
Alfalfa	48	11	53	5.5
Grass	25	10	38	2.0

[1] From EB0161

Readily soluble fertilizers (e.g. potassium sulfate) are more easily lost from soil than others. Phosphate fertilizers can become tied up as minerals which are minimally plant available. See EB0188 for information on specialized P fertilizers. The decision of which source to apply should be selected based on cost per pound of available nutrient, ease of application, and potential germination issues if seed-applied.

If available, manure may be the most economical P and K source. Because manure nutrient content is highly variable, test the manure and soil for nutrient content to calculate application rates that meet crop needs. Manure may contain more P and K than grasses' annual needs and can be used to bank P and K in the soil. However, the high N concentration may reduce N fixation in legumes. The Natural Resources Conservation Service (NRCS) can help with rate calculations, or see MT4449-13. Be aware that manure can contain viable weed seeds or herbicide residues toxic to forage species.

Grazing livestock return 60-90 percent of the nutrients they consume to the soil via manure and urine. However, nutrients are redistributed from grazing areas to areas near corners, fences and water. This can eventually lead to nutrient deficiencies in preferred grazing locations *(3)*. For a summary of using manure as a nutrient source see EB0200 and reference *4*.

TABLE 5. Plant part to sample, sampling time and critical nutrient concentrations for plant tissue from alfalfa and grass[1].

	Alfalfa	Grass
Plant part	Leaves from top third of plant	Uppermost leaves
Stage	Bud to 10% bloom	Right before heading
Element (units)	Nutrient concentration range[2]	
Phosphorus (%)	0.25-0.70	0.23-0.35
Potassium (%)	2.00-3.50	2.60-3.50
Sulfur (%)	0.25-0.50	0.20-0.25
Boron (ppm)	30-80	8-12
Copper (ppm)	10-30	3-5
Iron (ppm)	30-250	50-200
Manganese (ppm)	30-100	50-150
Zinc (ppm)	20-70	20-50

[1] Abbreviated from *5;* [2] Nutrient concentration range is valid only for the crop, plant part, and sampling time indicated.

Rate The correct balance among N, P, K and S is important for effective nutrient use by plants. Soil tests should provide the basis for P, K and micronutrient fertilization rates and can detect a nutrient deficiency before yield is compromised (see MT200702AG).

The fertilizer rate suggestions presented in this bulletin and EB0161 are based on a "sufficiency" fertilizer rate which is the minimum amount required to optimize net revenue in the current year. In general, if soil fertility is low, add nutrients to meet sufficiency levels. If soil tests indicate fertility is optimal, consider applying the amount removed by harvest (Table 4). If nutrient levels are above optimal, no additional fertilizer is needed.

Unfortunately, soil tests for sulfate-S are not a reliable indicator of plant available S. Therefore, plant tissue analysis is the best tool to determine S status and a valuable tool for in-season management of other nutrients (Table 5). The critical tissue nutrient concentration is the level at which approximately 90-95 percent of maximum yield is obtained and varies with growing conditions. Because tissue concentrations change with plant maturity, it is important to sample the correct tissue at the correct time. Plant and soil samples taken from an affected area can be compared to healthy samples to help identify a limiting nutrient.

Visual plant nutrient deficiency symptoms can also be used to manage nutrients. However, it is better to rely on soil test recommendations, nutrient removal rates, or periodic tissue nutrient concentrations, because once nutrient deficiency symptoms appear, yield has likely already been reduced. If deficiency symptoms are observed, in-season fertilizer of readily available nutrients such as sulfate-S is warranted if applied before stem elongation in grasses or mid-vegetative stage in alfalfa.

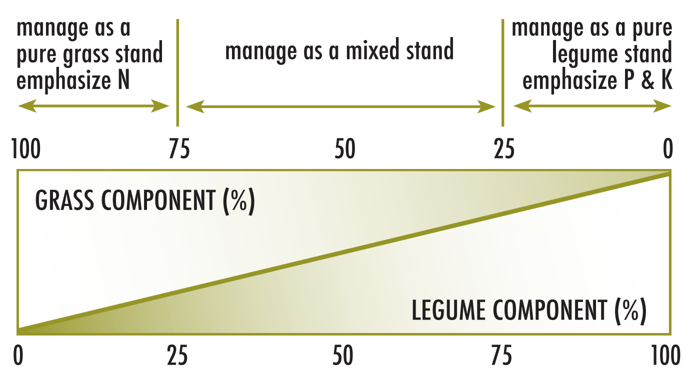

FIGURE 1. Nutrient focus depends on ratio of grass to legumes in the stand. Adapted from *6*.

After that point, it may be too late to affect yield. See MT4449-9 for more information. Be cautious of pseudo-deficiencies, such as disease or herbicide damage, that may look like a nutrient deficiency.

Producers can assess their fertilizer or manure application rates by dividing a field into strips, incrementally increasing fertilizer rates, and evaluating forage response.

In general, nutrient management depends on the grass to legume ratio in the stand. If a stand contains more than 75 percent legume, then emphasize P and K (Figure 1). Sufficient K is important to maintain legumes in mixed stands (Figure 2). If K is limiting alfalfa, then adding P without K over several years may be less economical than adding no P or K at all. Fields receiving P annually for five years without K were abandoned at the third and fourth harvest of the fifth year due to low yield and weed invasion. In contrast, yields on the plots receiving no P or K and P plus K were still providing yields worth harvesting (Figure 3). The cumulative effect of P and K imbalance had severe consequences for alfalfa survival and production.

The balance between nutrients also affects forage quality, including forage content of critical micronutrients for animal health *(8)*. Forage mineral concentrations are sometimes lower than required for animal production *(9)*, as when insufficient magnesium leads to grass tetany. However, micromanaging forage nutrient content through precise fertilization is impractical. Be aware that soil fertility influences forage nutrient content; therefore, test forage quality, adjust soil fertility if advised, and use supplements for animals to correct deficiencies.

Phosphorus Most Montana soils are low in plant available P, in part because high calcium levels tie up P. Apply P based on periodic soil tests (Table 2), rather than projected annual yield. Legumes require about 50 percent more P than grasses for optimal N-fixation, healthy production, and stand longevity, even though the amount of P removed per ton is about the same for alfalfa and grass (Table 4). The additional amount of P required by legumes over grasses increases as the soil P level decreases.

Forage is most likely to respond to additional P when soil levels are low. On irrigated alfalfa in Utah, spring broadcast MAP only increased yields when the soil P level was low (Olsen P = 4.0 ppm in top foot) and not when levels were moderate (Olsen P = 7.8 ppm), even though the application rates were based on soil test recommendations (Figure 4, page 5). However, because P is not lost to groundwater or air like N can be, a single large P application can supply crops for several years, even in calcareous soils *(11)*. This gives producers the opportunity to bank soil P levels when P fertilizer costs are low. On a dryland grass/legume mix in Saskatchewan, 41 lb P_2O_5/acre applied three years in a row benefitted yield for another three years *(12)*. A 25-year-old crested wheatgrass stand in southwestern Saskatchewan benefited from a single 100 lb P_2O_5/acre treatment 10 years after application *(13)*. Crops can only benefit from residual P if other nutrients are not limiting.

Potassium Both legumes and grasses depend on K for winter hardiness and persistence. However, plant tissue K concentrations desired for optimal plant growth may be higher than two percent and unsafe for livestock consumption *(14)*.

FIGURE 2. Adding K (left) to alfalfa/grass mix favors alfalfa, whereas no K (right) favors grasses.

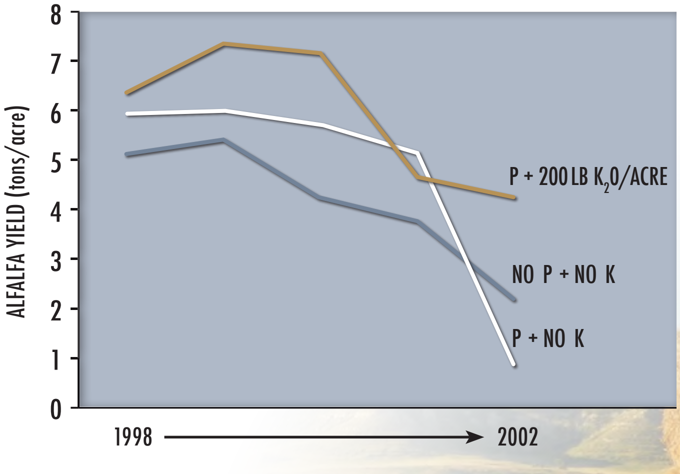

FIGURE 3. Five years of annual imbalanced P and K fertilization reduced alfalfa yields. Yields are averaged over annual applications of 50, 100, and 150 lb P_2O_5/acre. Indiana *(7)*.

Legumes need more K than grasses because they require K for N-fixation. Potassium-limited alfalfa stands lose plant and stem density as well as shoot mass which all reduce yields *(15)*. In contrast, grasses can persist for a few years with low K availability *(16)*. Hay production removes a large amount of K and stand health depends on sufficient K; however, because of potential livestock toxicity, it is especially important to soil test to determine K fertilization rates.

Sulfur can be deficient in areas where it is not part of the parent rock material. Deficiency is becoming more common because S is no longer a 'contaminant' in other fertilizers, coal and oil are burning cleaner, and higher yielding crop varieties are removing more S from the soil. Sulfur is required for N-fixation by legumes, optimal use of N in non-legumes, and making protein. Therefore, poor S nutrition can lead to low yields, forage protein content, and digestibility. Adding 25 lb S/acre to the N-P-K (50-100-50) fertilizer mix on dryland alfalfa and alfalfa/grass in central Montana increased forage protein by about one percentage point *(17)*. Because S helps convert nitrate to protein, S additions may help decrease forage nitrate concentrations (Figure 5, page 5).

As mentioned earlier, plant S status is best determined through plant tissue analysis (Table 5) or nutrient deficiency symptoms. While grass forage is S deficient at tissue levels below 0.20-0.25 percent, it is possible to cause livestock health problems with forage S levels greater than 0.30 percent. Since adequate S and N are both needed to make protein, the N:S ratio is also a potential indicator of plant-S status, but only if N is sufficient. Grasses may be S-deficient at N:S greater than about 15:1, while alfalfa is S-deficient at N:S ratios above 17:1.

Sulfur can be maintained with applications of elemental S every few years to replace S removed by harvest (Table 4). Grazing removes less S from a field than hay because livestock return 85-90 percent of the ingested S back to the soil in feces and urine, although unevenly distributed *(19)*. Alfalfa requires and removes more S than grasses. Annual applications of 45 lb S/acre sustained high alfalfa yields and protein in Manitoba *(20)*. If tissue concentrations are low or the stand appears S deficient, an in-season application of sulfate-S at 10-20 lb S/acre can alleviate S-deficiency for legume-grass mixtures.

Micronutrients Extreme care is required when applying micronutrients because some (especially boron) can be toxic. The response to micronutrient fertilization depends on the crop and micronutrient (Table 6). Fertilizer rate depends on the micronutrient and its form (Table 7). Micronutrient fertilizers are not recommended without a soil test or plant tissue analysis (Table 5) and consulting with either a forage or soil specialist. For more information on micronutrients, see: EB0161, MT4449-9, MT4449-7 and reference *24.*

Timing and Frequency Timing of fertilizer application generally depends on the source and mobility of the nutrient in the soil, and soil and climatic conditions which influence the rate at which nutrients

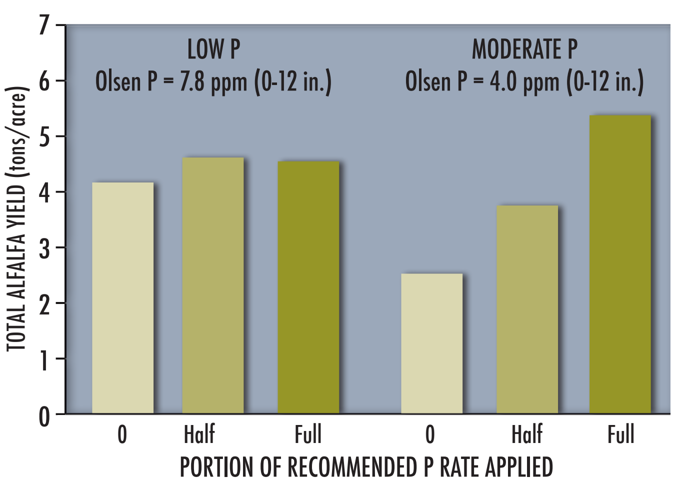

FIGURE 4. Alfalfa yield in Iron County, Utah, after spring broadcast MAP at half and full application rates determined by soil test recommendations in two years with different soil P levels *(10)*.

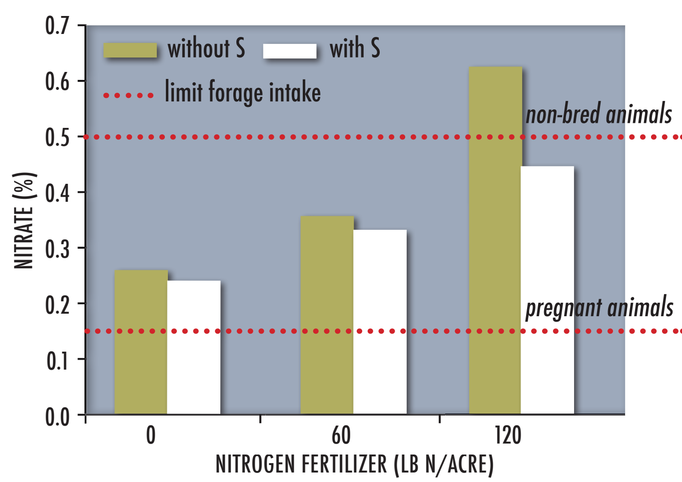

FIGURE 5. At high N rates, adding 20 lb S/acre kept Haybet barley forage nitrate to levels below those toxic to non-pregnant livestock.

become and remain available from fertilizer. Sources that slowly release their nutrients over time or are immobile in the soil should be applied well before they are needed by the plant. In established stands, apply P or K after the last cutting and just before the critical fall period when root carbohydrate reserves are being built up. A few years' worth of P can be applied before seeding or onto established stands. A single P application on 3-year-old alfalfa at 100-400 lb P_2O_5/acre produced forage yield, protein and net economic returns similar to the same amount of P divided over five annual applications *(25)*. It is best to split K application between the first and last cuttings to ensure the first harvest does not take up more than it needs (luxury consumption) and promote good stand health going into winter *(15)*.

Sources that supply readily available mobile nutrients (e.g. chloride and sulfate) should be applied shortly after green-up. This ensures adequate nutrient supplies for rapid growth, because the greatest nutrient need generally comes just prior to biomass increases. For example, alfalfa has taken up 40-50 percent of its S when it has only produced 20 percent of its biomass *(26)*. Another option is split applications during the growing season, which helps increase nutrient recovery.

TABLE 6. Relative response of alfalfa and grass to micronutrient fertilizers when soil levels are low *(21)*.

	------------------ Response --------------------				
Crop	Boron	Copper	Iron	Manganese	Zinc
Alfalfa	High	High	N/A	Low	Low
Grass	Low	Low	High	Medium	Low

Method Application method should be selected to maximize crop fertilizer uptake with minimal plant disturbance. In general, weed monitoring and control measures are more important with surface than subsurface application methods.

Because P is immobile, it is more effective when placed into the rooting zone than on the soil surface, especially when the soil is very P deficient, under moisture-limited conditions, or at low P application rates *(25)*. However, subsurface banding of alfalfa or grasses has not consistently increased yields more than broadcast application, partially because it is disruptive to the stand *(20, 27)*. Subsurface banding with a narrow disk opener helps reduce plant damage *(28)*. Under irrigated conditions, surface applications may be better than subsurface applications because roots near the surface are able to take up surface applied P, alfalfa crowns can take up P, and there is less stand damage. Potassium is more mobile than P, so placement method on established stands is less important.

Foliar application is useful for in-season adjustment of nutrients if leaf burn is minimized. The risk of leaf burn increases when N is added to the mix and with high air temperatures *(29)*.

From research with wheat, foliar P is more beneficial in low than high yielding years, because moisture stressed roots are not taking up P through the soil and some foliar applied P does get taken up through the leaf *(30)*. Under irrigated conditions, foliar P on alfalfa has not produced higher yields than broadcast granular P *(31)*.

TABLE 7. General micronutrient application guidelines if nutrients are deficient *(22)*.

			---------- Rate (lb/acre) ----------		
Nutrient	Fertilizer Form	Timing	Broadcast and Incorporate	Seed-placed[1]	Foliar
Boron	Sodium borate	Spring	0.5 – 1.5	NR[2]	0.3 – 0.5
Copper	Sulfate	Spring or Fall	3.5 – 5.0	NR	NR
	Oxysulfate	Fall	5.0	NR	NR
	Chelated	Spring	0.5	0.25 – 0.50	0.20 – 0.25
Iron[3]	Chelated	Spring	NR	NV	0.15
Manganese	Sulfate	Spring	50 – 80	4 – 20	NR
	Chelated	Spring	NR	NR	0.5-1.0
Zinc	Sulfate	Spring or Fall	3.5 – 5.0	NR	NR
	Oxysulfate	Fall	5 – 10	NR	NR
	Chelated	Spring	1	NV	0.3 - 0.4

[1] Subsurface band is not recommended for any of these fertilizers; [2] NR – not recommended, NV – not verified; [3] *23*

Iron, copper, manganese and zinc are very immobile and unavailable to the plants if broadcast, unless incorporated before seeding. Foliar applications of micronutrients may be a practical and economical way to correct deficiency *(32)* primarily because plants need so little that enough nutrients may enter through the leaf. Placement method of mobile micronutrients such as chloride and boron is less important because irrigation and/or rainfall will move mobile nutrients to the roots.

SHOULD I FERTILIZE?

Because the relatively immobile nutrients can be banked in the soil for later use, know your soil nutrient levels and consider adding these when fertilizer prices are lower. Dryland forage is generally managed for sustainable, low-input, long-term production to overcome drought periods, rather than for prime quality hay. Adequate P and K are key to sustaining stand health and most likely less expensive than reseeding or interseeding.

SUMMARY

Forage yield and quality can be improved with good soil fertility management. If stands are largely desirable species, rejuvenating old forage stands with fertilizer is more effective than mechanical rejuvenation methods such as aeration or harrowing and generally less expensive than reseeding. The correct balance between nutrients can influence species composition and is important for efficient fertilizer use and forage yield and quality. Base fertilizer rates on soil tests or plant tissue concentrations to ensure adequate amounts, yet minimize the risk of forage nutrient concentrations that are toxic to livestock. Nutrient sources that slowly release their nutrients over time can extend benefits season-long or over years. They should be applied well before they are needed by the plant. Sources that supply readily available nutrients that are mobile in the soil should be applied shortly before the period of maximum plant nutrient uptake. Well thought out nutrient management on forages can easily pay for itself.

REFERENCES

1. Entz, M.H., V.S. Baron, P.M. Carr, D.W. Meyer, S.R. Smith, Jr., and W.P. McCaughey. 2002. *Potential of forages to diversify northern Great Plains cropping systems.* Agronomy Journal. 94:240-250.
2. Wichman, D. Personal communication. Superintendent and Research Scientist. Central Agricultural Research Center, Montana State University, Moccasin, Montana.
3. Schnyder, H., F. Locher, and K. Auerswald. 2010. *Nutrient redistribution by grazing cattle drives patterns of topsoil N and P stocks in a low-input pasture ecosystem.* Nutrient Cycling in Agroecosystems. 88:183-195.
4. Saskatchewan Ministry of Agriculture. 2008. *Fertilizing Forages with Manure.* http://www.agriculture.gov.sk.ca/Default.aspx?DN=feb4e9af-8270-440d-8739-5bd40cb6b344
5. Beegle, D. 2002. *Soil Fertility Management for Forage Crops: maintenance.* Agronomy Facts 31-C. Penn State Extension. http://extension.psu.edu/plants/crops/forages/soil-fertility/soil-fertility-management-for-forage-crops-maintenance
6. Flore, N. 2003. *Fertility management in forages.* Saskatchewan Soil Conservation Association Conference. February 19-20. Saskatoon, Saskatchewan. pp. 78-87. http://www.ssca.ca/conference/conference2003/Flore.pdf
7. Berg, W.K., S.M. Brouder, B.C. Joern, K.D. Johnson, and J.J. Volenec. 2003a. *Improved phosphorus management enhances alfalfa production.* Better Crops. 87:20-23.
8. Hemingway, R.G. 1999. *The effect of changing patterns of fertilizer applications on the major mineral composition of herbage in relation to the requirements of cattle: a 50-year review.* Animal Science. 69:1–18.
9. Grings, E.E., M.R. Haferkamp, R.K. Heitschmidt and M.G. Karl. 1996. *Mineral dynamics in forages of the Northern Great Plains.* Journal of Range Management. 49:234-240.
10. Koenig, R., D. Winward, C. Reid, J. Barnhill, M. Pace, and K. Heaton. 2009. *Phosphorus source and surface fluid band spacing effects on irrigated alfalfa.* Soil Science Society of America Journal. 73:367-374.
11. Halvorson, A.D. and A.L. Black. 1985. *Fertilizer phosphorus recovery after seventeen years of dryland cropping.* Soil Science Society of America Journal. 49:933-937.

12. Nuttall, W.F., D.A. Cooke, J. Waddington, and J.A. Robertson. 1980. *Effect of nitrogen and phosphorus fertilizers on a bromegrass and alfalfa mixture grown under two systems of pasture management. I. Yield, percentage legume in sward, and soil tests*. Agronomy Journal. 72:289-294.

13. Read, D.W.L. and G.E. Winkleman. 1982. *Residual effects of nitrogen and phosphorus fertilizer on crested wheatgrass under semiarid conditions.* Canadian Journal of Plant Science. 62:415-425.

14. Crawford, G. 2007. *Avoiding Mineral Toxicity in Cattle.* University of Minnesota Extension. http://www.extension.umn.edu/agriculture/beef/components/docs/avoiding_mineral_toxicity_in_cattle.pdf

15. Berg, W.K., S.M. Brouder, B.C. Joern, K.D. Johnson, and J.J. Volenec. 2003. *Enhancing alfalfa production through improved potassium management.* Better Crops. 87:8-11.

16. Cherney, J.H. and D.J.R. Cherney. 2005. *Agronomic response of cool-season grasses to low-intensity harvest management and low potassium fertility.* Agronomy Journal. 97:1216–1221.

17. Wichman, D. 2001. *Fertilizer Use on Dryland Perennial Forages.* Fertilizer Fact No.27. Montana State University Extension, Bozeman, Montana. http://landresources.montana.edu/fertilizerfacts/27_Fertilizer_use_on_dryland_Perennial_forages.HTM

18. Westcott, M. Unpublished data. Retired Superintendent. Western Agricultural Research Center, Montana State University, Corvallis, Montana.

19. Saggare, S., M. Hedley, and S. Phimsarn. 1998. *Dynamics of sulfur transformations in grazed pastures.* In: Sulfur in the Environment. D.G. Maynard [Ed]. Marcel Dekker, Inc. New York, NY. pp. 45-94.

20. Malhi, S.S., K.S. Gill, D.H. McCartney, and R. Malmgren. 2004. *Fertilizer management of forage crops in the Canadian Great Plains.* Recent Research Developments in Crop Science. 1:237-271.

21. Voss, R. 1998. *Micronutrients.* Iowa State University, Ames, Iowa. http://www.agronext.iastate.edu/soilfertility/info/Micronutrients_VossArticle.pdf

22. Karamanos, R.E. 2000. *Micronutrients - update 2000.* Proceedings of the Soils and Crops 2000 Workshop. pp. 334-352. February 24-25. Extension Division, University of Saskatchewan, Saskatoon, Saskatchewan.

23. Gerwing, J., and R. Gelderman. 2005. *Fertilizer Recommendation Guide.* South Dakota State University Cooperative Extension Service. EC750. http://pubstorage.sdstate.edu/AgBio_Publications/articles/EC750.pdf

24. McKenzie, R. 2001. *Micronutrient Requirements of Crops.* Alberta Agriculture and Rural Development. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex713

25. Malhi, S.S., R.P. Zentner, and K. Heier. 2001. *Banding increases effectiveness of fertilizer P for alfalfa production.* Nutrient Cycling in Agroecosystems. 59:1–11.

26. Pumphrey, F.V. and D.P. Moore. 1965. *Sulfur and nitrogen content of alfalfa herbage during growth.* Agronomy Journal. 57:237-239.

27. Bauder, J.W., D.J. Sieler, S. Mahmood, and J.S. Jacobsen. 1998. *Extending phosphorus fertilizer benefits in established alfalfa.* Better Crops. 82:24-25.

28. Malhi, S.S. 1997. *A special banding technique increases effectiveness of phosphorus fertilizer on alfalfa.* Better Crops. 81:9-11.

29. Phillips, S.B. and G.L. Mullins. 2004. *Foliar burn and wheat grain yield responses following topdress-applied nitrogen and sulfur fertilizers.* Journal of Plant Nutrition. 27:921–930.

30. Mosali, J., D. Kefyalew, R.K. Teal, K.W. Freeman, K.L. Martin, J.W. Lawles, and W.R. Raun. 2006. *Effect of foliar application of phosphorus on winter wheat grain yield, phosphorus uptake, and use efficiency.* Journal of Plant Nutrition. 29:2147–2163.

31. Reid, C.R., D.L. Winward, and R.T. Koenig. 2004. *A comparison of liquid phosphoric acid and dry phosphorus fertilizer sources for irrigated alfalfa production on calcareous soils.* Communications in Soil Science and Plant Analysis. 35:39-50.

32. Malhi, S.S., L. Cowell, and H.R. Kutcher. 2005. *Relative effectiveness of various sources, methods, times and rates of copper fertilizers in improving grain yield of wheat on a Cu-deficient soil.* Canadian Journal of Plant Science. 85:59-65.

FOR MORE INFORMATION

MSU EXTENSION PUBLICATIONS

These, and many others, can be found by title under 'Extension publications' http://landresources.montana.edu/soilfertility/, or by contacting MSU Extension Publications at (406) 994-3273, http://store.msuextension.org.

Dryland Pastures in Montana and Wyoming Species and Cultivars, Seeding Techniques and Grazing Management. EB0019.

Enhanced Efficiency Fertilizers. EB0188.

Fertilizer Guidelines for Montana Crops. EB0161.

Interpretation of Soil Test Reports. MT200702AG.

Montana Cool-Season Pulse Production Guide. EB0210.

Nitrate Toxicity of Montana Forages. MT200505AG. (currently out of print)

Soil Nutrient Management for Forages: Nitrogen. EB0216.

Soil Nutrient Management on Organic Grain Farms in Montana. EB0200.

Species Selection, Seeding Techniques and Management of Irrigated Pastures in Montana and Wyoming. EB0099.

NUTRIENT MANAGEMENT MODULES

The following publications, and others in the series, can be found online at http://landresources.montana.edu/nm or by contacting MSU Extension Publications at (406) 994-3273, http://store.msuextension.org.

MT4449-2. *Plant Nutrition and Soil Fertility.*

MT4449-4. *Phosphorus Cycling, Testing and Fertilizer Recommendations.*

MT4449-5. *Potassium Cycling, Testing and Fertilizer Recommendations.*

MT4449-6. *Secondary Macronutrients: Cycling, Testing and Fertilizer Recommendations.*

MT4449-7. *Micronutrients: Cycling, Testing and Fertilizer Recommendations.*

MT4449-9. *Plant Nutrient Functions and Deficiency and Toxicity Symptoms.*

MT4449-13. *Manure and Biosolids: Regulation and Management.*

OTHER RESOURCES

Colorado Forage Guide. 2012. http://www.ext.colostate.edu/sam/forage-guide.pdf

National Forage Testing Association. http://www.foragetesting.org/

Natural Resources Conservation Service (NRCS) Manure Management Planner. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/mt/technical/ecoscience/manure/?cid=stelprdb1167155

University of Idaho Extension. Idaho Forage Web page http://www.extension.uidaho.edu/forage/

University of Idaho Extension. Managing Nutrients for Forage Crops Web page http://www.extension.uidaho.edu/nutrient/crop_nutrient/forages.html

ACKNOWLEDGEMENTS

We thank the following for their time and expertise in reviewing this bulletin:

- Joe Brummer, Associate Professor, Department of Soil and Crop Sciences, Colorado State University
- Paul Dixon, Agriculture and Natural Resource Specialist, Dixon Land Management, Sheridan, WY.
- Marc King, Montana State University Extension Agent, Sweetgrass County, MT
- Dave Wichman, Superintendent and Research Scientist, Montana State University, Central Agricultural Research Center, Moccasin, MT
- MSU Extension Communications & Publications for design and layout

MONTANA STATE UNIVERSITY EXTENSION