Heart of America Grazing Conference
Presenters

In Defense of Soil Health

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Soil health is a hot topic today in sustainable agriculture circles and is even becoming more popular in conventional agriculture. However, the term is often thrown around loosely, and sometimes the meaning gets muddled.

I give a lot of presentations at conferences and conduct workshops around the country on soil health practices. What we are finding is that, despite all the attention, fewer than 10 percent of farmers and grazers around the U.S. have adopted sound soil health practices. Most are still somewhat skeptical and have a hard time grasping the benefits to be gained from building true health within their soils.

I hear many objections from farmers and grazers about shifting practices to promote soil health. If this works so well, why isn't everyone doing it? What will it cost me? I'm too busy to implement any of those practices.

But the biggest question I get is this: "Where is the scientific data supporting all these claims of benefits?"

That data does indeed exist. Many studies published in peer-reviewed journals support the benefits of soil health, along with the farming and grazing practices that enhance soils. I'll discuss some of the data while pointing you toward the research.

Benefits of soil health practices

To understand the benefits of soil health practices, we first must recognize that all plant growth is highly correlated to soil life.

Research conducted at New Mexico State University revealed that the soil's fungi-to-bacteria population ratio has greater influence on plant biomass production and yield than does inorganic nitrogen (N) or phosphorus (P) applications (Johnson, et. al., 2012).

Soil bacteria and fungi perform much of the decomposition of organic matter at the soil surface, providing significant nutrients for growth health and growth. Researchers have found that fungi are more efficient than bacteria at decomposing and storing nutrients (Bardgett & McAlister, 1999; De Vries, et.al., 2006). It has been demonstrated that higher fungal populations increase the soil's ability to hold carbon, to create a readily available nutrient pool and to buffer against low pH conditions.

This makes the soil fungi:bacteria ratio a reliable measure of overall soil health improvement and soil carbon sequestration (Beare et al., 1992; Yeates et. al., 1997; Bailey et al., 2002).

The New Mexico State study found that when farmers planted highly diverse cover crops between plantings of cash crops, they were able to produce similar or even higher yields with reduced reliance upon synthetic fertilizers. The results showed that essential minerals and trace elements in the soil increased as cover crop diversity increased due to carbon inputs from the living plants stimulating microbial activity.

This in turn increased soil aggregation and soil macro- and micronutrient availability, while improving soil water-holding capacity. The system creates a positive feedback loop, similar to the endocrine loop found in animals and humans.

Interestingly, Johnson's group discovered that as cover crop diversity and biomass production increased, the effects in the soil were exponential, as improvements multiplied throughout the system. This is due to ever-increasing synergies between soil microbial populations and the plants they serve.

Dr. Christine Jones (WANTFA New Frontiers in Agriculture, Sept. 2013) found that the more closely we mimic the structure and function of year-round ground cover, the more productive our farms will be. Jones' work indicates that the more species included in the ground cover, the better.

Multi-species cover crops help restore below-ground diversity and soil biological function, including increases in atmospheric N fixation and making bound phosphorus soluble. These effects improve overall plant productivity and yields. Her work showed that the increases in nutrient sourcing and soil moisture retention through planting diverse cover crops builds soil nutrients in successive years.

Similarly, research has shown that grassland ecosystems need year-round cover to protect from soil loss and facilitate soil microorganism function. Plant and litter cover provide numerous documented benefits such as enhanced soil microbial activity, soil aggregate stability, increased soil organic matter, improvements in water infiltration rates, decreased soil water evaporation and soil temperature buffering.

These benefits result in enhanced plant nutrient status and nutrient availability, improved plant growing conditions and increases in soil organic matter (Thurow,1991; Rietkerk, et. al., 2000; Bardgett, 2005).

Results of Poor Management Practices

Researchers have found that poor farming and grazing management can inhibit soil-building processes and even cause soil degradation. Soil loss can result from grazing that causes excessive plant removal and trampling. These researchers also found that frequent use of fire ("patch burning", pasture burning) inhibited soil building, as did excessive drought conditions (Thurow, 1991; Wright & Bailey, 1982).

Thurow (1991) found that as the amount of bare ground increased due to poor management practices, proper soil function decreased and erosion risk increased substantially.

One of the biggest mistakes we make in agriculture is creating bare ground. Research has documented that bare ground suffers significant declines in soil microbial activity and organic matter, with subsequent increases in erosion. Plant diversity and density dissipates the energy of raindrops before they contact the soil and cause erosion. (Blackburn, 1975; Blackburn, et. al., 1986).

Poor soil management practices cause soil degradation due to increases in soil compaction and bulk density, leading to reductions in water penetration and soil aggregate stability (Herrick et. al., 1999; Herrick & Jones, 2002). Neary and co-workers (1999) and Wright & Bailey (1982) found that conditions allowing for elevated soil temperatures and soil loss negatively affect water infiltration rates, nutrient retention and biological function, while increasing the rate of water evaporation from the soil.

Researchers in Australia discovered that at the time of European settlement, the hot and dry southern half of the continent supported significantly more warm season (C4) grasses and forbs than it does today. Even with temperatures routinely climbing above 100^{o} F and little rain, the original groundcover remained green throughout the summer season due to greater water holding capacity of the soils.

Poor grazing practices after European settlement devastated the forb population and reduced the number of grass species, resulting in reduced plant populations and increased soil exposure (Presland, 1977).

In the U.S., poor grazing practices and excessive tillage have significantly reduced water-holding capacity and reduced broadleaf plant (forb) populations. The original groundcover across the Great Plains of North America contained far more broadleaf plants than grasses, with numerous summer-active legumes and forbs.

Broadleaf plants stimulate far greater nutrient cycling and microbial diversity than grasses alone. Scientists found that poorly managed grazing and excessive tillage significantly reduced broadleaf plant populations across much of the Great Plains. With unmanaged grazing, ruminants selected the broadleaf plants that were the most palatable and nutrient-dense and grazed them out of existence in much of the landscape (Lunt, et. al., 1998).

Realizing Benefits From Soil Health Management

Studies have shown that the amount and type of vegetation covering the soil significantly influences all soil physical parameters and hydrological properties. Benefits increase as you progress from bare soil, to short grasses, to bunch grasses and forbs interspersed with woody plants.

A mixed plant population of bunch grasses, broadleafs and woody plants produces significantly greater amounts of foliage and root biomass — especially when compared to monocultures, short grasses, annuals and improved cultivars — resulting in greater soil organic matter and microbial species diversity and density (Blackburn, 1975; Milne & Haynes, 2004; Pluhar et. al., 1987; Thurow, 1991; Thurow, et. al., 1986, 1987).

Devi and Yavada (2006) found that aboveground plant litter/cover aids soil moisture micro-environments and creates more consistent soil temperatures. These conditions favor greater soil microorganism activity. In addition, they tend to enhance the formation of stable soil aggregates, which aids water infiltration and improves soil fertility (Herrick, et. al., 1999).

Approximately 60% of all soil organic matter (SOM) is comprised of soil organic carbon (SOC) that positively influences all chemical, physical and biological functions of soil health (Bardgett, 2005). Increases in SOC result in increased soil aggregate stability, water-holding capacity and Cation Exchange Capacity (CEC).

As organic matter increases, the ability of the plant to take up nutrients and trace elements also increases, nutrient leaching is reduced, soil pH is buffered and plant growth is enhanced. Scientists have found that SOM profoundly impacts plant biomass production and health, water quality and availability, carbon sequestration and overall soil health (Charman & Murphy, 2000; Lal, 2008).

Land management practices significantly affect the ability of the soil to sequester and retain organic carbon. Carbon sequestration is accelerated by practices that enhance plant growth on a year-round basis, lower incidence of bare or partially exposed soil, and stimulate extensive root growth and microbial growth. (Parton et. al., 1987).

Adaptive Grazing Practices Produce Dividends

In a direct comparison of adaptive multi-paddock (AMP) grazing with light continuous (LC), heavy continuous (HC) and non-grazing (EX), researchers found that AMP grazing produced the highest levels of soil carbon, the greatest plant biomass production and the least amount of bare soil. The LC and HC grazing practices had lower plant biomass production, greater degrees of bare soil, and decreased soil water-holding capacity than AMP and EX (Teague, et. al., 2011; Allen, 2007; Leake, et. al., 2004).

These results are consistent with prior studies showing that soil carbon availability is regulated through plant biomass production and soil coverage (Conant, et. al., 2001: Jones & Donnelly, 2004). Earlier work conducted by Thurow (1991) demonstrated that AMP grazing at higher stock densities on semi-arid rangeland provided more positive impacts on soil physical properties and soil water infiltration compared to continuous grazing at the same stocking rate.

In earlier work, Teague and co-workers (2010) found that AMP grazing produced greater forage biomass production, maintained adequate ground cover with far less exposed soil, increased soil aggregate stability, lowered soil temperatures, and sequestered more soil carbon than other methods of grazing or non-grazing.

Soil chemistry parameters also were improved with AMP grazing. Soil CEC was higher when AMP grazing was employed instead of light continuous, heavy continuous or non-grazing, which is consistent with differences in soil carbon effects.

As CEC increases, the ability of the soil to retain nutrients and water increases. Soil pH was buffered when soil microbial responses were increased with AMP grazing. In addition, magnesium and sodium levels in the soil were improved with AMP grazing, as was the rate of nutrient cycling.

A primary reason for these nutrient cycling improvements was that AMP grazing encouraged deeper root penetration, allowing the roots and the associated mycorrhizal fungi to reach mineral stores deeper in the soil (Teague, et. al., 2011). AMP grazing practices produced the greatest fungi:bacteria ratio when compared to other grazing methods or non-grazing (Teague, et. al., 2010; Teague, et. al., 2011).

Better soil management practices, which include AMP grazing, create favorable species changes in the plant community. In turn this creates more favorable soil microbial compositions. Soil biota function is enhanced, triggering natural feedback mechanisms (Coleman & Crossley, 1996).

Bardgett (2005) found that enhancing interactions between plants and soil biota drives ecosystem function and productivity, as well as providing pivotal structuring forces in the plant community. Bardgett's work showed that plant-soil biota interactions increased the microbial breakdown of plants, making nutrients more readily available, enhancing plant root exudate production, increasing fungal associations with plant roots, and positively altering the physical structure of the soil to allow for increased water and nutrient movement.

Roundup toxic to soil fungus

A recently released study published in Environmental Science and Pollution Research found that Roundup is toxic to soil fungi, even at application rates well below recommendations.

The study discovered that at application rates diluted 100 times more than those typically used in agriculture, Roundup caused 50% mortality in the soil filamentous fungus Aspergillus nidulans. This is important, as Aspergillus nidulans is frequently used as a marker of soil health, thus pointing to the possibility that Roundup is causing more widespread damage (Nicolas, et. al., 2016).

Even more disturbing is the finding that the commercial formulation of Roundup appears to have greater toxicity than glyphosate alone, indicating that the additives are not necessarily inert. The research found that Roundup impaired soil fungi growth, increased cellular disturbances and interfered with cellular energy and respiratory metabolism.

The report went on to note that soil microorganism energy metabolism and respiratory function disturbance were detected at doses producing no visible effect to the naked eye. The researchers said this implies that even the residues in GM herbicide-tolerant crops may be causing detrimental effects.

Since soil microorganisms are critical to soil health, and Roundup is the most frequently used herbicide worldwide, soil fungi populations in many countries and across broad landscapes have been damaged.

Diversity and Complexity in Our Pastures: Does it Matter?

The vast majority of established pastures in the U.S. are dominated by what I would term a "near monoculture", meaning that most of the forage yield, or biomass production, is obtained through two to three primary forages in the mix.

Natural prairies are a different story, as we see literally scores of plant species in mixes consisting of grasses, legumes and forbs. I have been on "species counts" in native prairie where experts identified more than 150 different plants, sometimes more than 200.

Does it matter whether our pastures are comprised of a near monoculture, or is managing for greater complexity and diversity important? Let's look at what some recent research tells us.

Penn State trial

A recent Pennsylvania State University study conducted at the Hawbecker Research Farm from 2005 to 2013 examined two- and five-species perennial mixes in terms of their impact on forage biomass production and soil organic carbon (SOC) analysis (Skinner and Dale, 2016).

In August 2004 the two-species pastures were sown into orchardgrass and white clover, while the five-species mix pastures were sown into orchardgrass, tall fescue, white clover, alfalfa and chicory. There were a total of four replications per treatment.

Grazing started in the spring of 2005 and continued through 2013. Paddocks in each treatment were grazed the same, with the number and class of animals varying between years and seasons, but with consistent stocking rates between treatments each grazing event.

Grazing started when the forage in each treatment reached 10 inches (25 cm) and stopped when the cattle had grazed down to 4 inches (10 cm). This resulted in five grazing events per treatment every year except 2006, when there were six. Grazing typically started in early to mid-May and ended in late October.

Forage biomass production was measured prior to each grazing by taking clippings and drying down, and comparing that amount of dry matter with what was measured again post-grazing.

Results showed that the five-species mix produced 31% more total forage biomass annually than the two-species mix, with the difference being more profound in wet years versus dry years. In other words, 31% more forage dry matter was available for livestock simply by having a little more diversity in the mix.

The five-species mix produced 34% greater forage biomass in the spring, 30% more in the summer, and 26% more biomass in the fall compared to the two-species mix. The five-species mix generally grew faster and recovered quicker between grazings, and was thus an average of 11.2 inches in height when a grazing event started, compared to 10 inches in the two-species paddocks. Since both treatments were grazed to the same residual height, the five-species mix paddocks had an additional 1.4 inches of forage growth removed with each grazing.

Soil organic carbon (SOC) was measured in alternate years from 2004 through 2012, with samples taken at six different soil depths (strata) starting at 2 inches (5 cm) down to 39 inches (100 cm). SOC accumulation down to 39 inches averaged 1.8 tons of carbon per hectare annually (0.72 ton/acre) with the five-species mix, compared to 0.5 ton of carbon per hectare annually (0.20 ton/acre) with the two-species mix. The most significant increases in SOC accumulation with the five-species mix occurred within the 4-8 and 8-12-inch strata.

The differences in both production and SOC remained strong throughout the nine-year period even though the five-species mix lost virtually all its chicory by 2008, and 95% of the alfalfa by 2012. So the residual effects of a five-species mix that became essentially a three-species mix were quite important.

Green Acres Trial

In a trial conducted by Green Acres Research Farm near Cincinnati, Ohio, annual cover crop cocktails called "biological primers" were planted in the spring of 2015. An 18-species, warm season cocktail mix developed by Dave Brandt at Walnut Creek Seeds was planted with a no-till drill on June 4, 2015. Just 55 days after planting, scientists at Green Acres measured 58,000 lbs. of wet forage biomass per acre. That translates into more than 8,000 lbs./acre forage dry matter.

Stocker calves were grazed using adaptive high stock density (AHSD) practices with daily moves on one-quarter to one-third acre paddocks. After the initial grazing, each paddock was rested approximately 30 days prior to re-grazing. Calculated forage dry matter (DM) for the second grazing was 4,500 lbs./acre. At the end of the warm season grazing period, the crop was terminated by intentionally overgrazing, and a 12-species cool season cocktail was no-tilled in for winter grazing.

Cattle performance and soil response were impressive. Cattle weighed before and after grazing the warm season cocktail gained an incredible 3.8 lbs./head/day. This was without the benefit of compensatory gain, as the cattle had just come off cool season perennial pasture.

Soil organic matter (SOM) increased from 3.6% to 4.4%, a total increase of 0.8%. The USDA-NRCS states that for every 1.0% increase in SOM, water holding capacity increases 25,000 gallons per acre. At the 0.8% gain, the SOM increase in this trial added 20,000 gallons/acre of water holding capacity. Over a 100-acre farm, that would be an additional 2 million gallons of water being absorbed into the soil with a moderate to heavy rainfall instead of running off or ponding and pooling.

Increases were also measured in soil nitrogen, soil mineral value, earthworm populations and soil microbial respiration (as measured by CO_2 release). Soil N increased 58 lbs./acre because N fixation from the atmosphere increased due to enhanced rhizobia activity from the legumes included in the 18-seed warm season mix.

Soil mineral value increased $105/acre due to the complex mix, adaptive grazing and enhanced microbial population. This is $105 less in spending on the external inputs required for similar performance. The earthworm population exploded to an estimated 130,000 per acre.

Soil microbial activity was measured indirectly using the Solvita method of measuring CO_2 respiration. Measurements showed a 44% increase in soil microbial activity, with CO_2 respiration rising from 128 to 186.

Self-Medicating – Provenza

Diverse and complex forage mixes also produce significantly more — and more diverse — secondary and tertiary nutrient compounds. We know much about primary compounds such as crude protein, calcium, potassium and magnesium, but there are also hundreds of nutrient compounds that are very important to the health of our animals, plants and soil. Different plant species produce different arrays of these compounds, and each has a specific role.

Dr. Fred Provenza has spent his academic career researching these compounds and their effects on the animal-plant-soil complex. His research shows that animals will purposely select for these compounds in their diet if given the opportunity.

Our problem is that we have often created situations where livestock cannot select from a broad array of secondary and tertiary nutrient compounds because our pastures do not have any complexity and diversity.

Dr. Provenza has shown that the medicinal benefits of these compounds are important in animal health and performance. For instance, some plants produce tannins, natural anti-parasites that can significantly reduce internal parasite loads in ruminant livestock (Lisonbee, et. al. 2009).

Livestock that consume plants containing tannins have lower fecal egg counts and nematode loads, and better animal gains (Niezen, et. al. 2002; Coop and Kyriazakis, 2001; Min and Hart, 2003; Min, et.al., 2004). Athanasiadon and co-workers (2000) found that tannins have a direct anthelmintic effect. Tannins also increase the supply of bypass protein in the gut (Reed, 1995; Foley, et.al., 1999) and enhance immune response to internal parasites (Niezen, et.al., 2002; Min and Hart, 2003).

Other studies show that foraging behavior is influenced by the availability of secondary and tertiary nutrient compounds in the diets of animals (Provenza and Villalba, 2006; Villalba and Provenza, 2007). Animals can self-medicate if given the opportunity (Huffman, 2003; Villalba, et.al., 2006).

Summary

So does plant species diversity and complexity in our pastures matter? The very short answer is "Yes".

We have to remember that in nature there are no singular effects. Everything we do in our management produces compounding and cascading effects whether we realize it or not. Selecting or planting for monocultures and near-monocultures produces compounding and cascading effects that reduce soil health, plant growth and animal performance. Selecting for complexity and diversity do just the opposite.

Conclusions

Soil health management practices and principles have numerous benefits that produce exponential effects. I often state during my presentations that nothing we do in agriculture has a singular effect. Every decision we make has compounding and cascading effects, whether for the good or for the bad.

The practices we implement on a day-to-day basis will have effects. It is up to us whether those effects are beneficial, or not.

References:

Allen, M.F., 2007. Mycorrhizal fungi: highways for water and nutrients in arid soils'. Soil Science Society of America. Vadose Zone Journal 6, 291–297, doi:10.2136/vzj2006.0068.

Bailey, V.L., Smith Jr., J.L., Bolton, H., 2002. Fungal-to-bacterial ratios in soils investi- gated for enhanced C sequestration. Soil Biology and Biochemistry 34, 997–1008.

Bardgett, R.D., 2005. The Biology of Soil: A Community and Ecosystem Approach.

Oxford University Press, New York.

Bardgett, R.D., McAlister, E., 1999. The measurement of soil fungal: bacterial biomass ratios as an indicator of ecosystem self-regulation in temperate meadow grass- lands. Biology and Fertility of Soils 29, 282–290.

Beare, M.H., Parmelee, R.W., Hendrix, P.F., Cheng, W., 1992. Microbial and faunal interactions and effects on litter nitrogen and decomposition in agroecosystems. Ecological Monographs 62, 569–591.

Blackburn, W.H., 1975. Factors influencing infiltration and sediment production of semiarid rangelands in Nevada. Water Resources Research 11, 929–937.

Blackburn, W.H., Thurow, T.L., Taylor, C.A., 1986. Soil erosion on rangeland. In: Proceedings Use of cover, soils and weather data in Rangeland Monitoring Sym- posium. Society for Range Management, Denver, CO, USA, pp. 31–39.

Coleman, D.C., Crossley, D.A., 1996. Fundamentals of Soil Ecology. Academic Press, London.

Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and con- version into grasslands: effects on soil carbon. Ecological Applications 11, 343–355.

Charman, P.E.V., Murphy, B.W., 2000. Soils, their Properties and Management, 2nd ed. Oxford University Press, Melbourne.

Devi, N.B., Yavada, P.S., 2006. Seasonal dynamics in soil microbial biomass, C, N and P in a mixed-oak forest ecosystem of Manipur, North-east India. Applied Soil Ecology 31, 220–227.

De Vries, F.T., Hoffland, E., van Eekeren, N., Brussaard, L., Bloem, J., 2006. Fun- gal/bacterial ratios in grasslands with contrasting nitrogen management. Soil Biology & Biochemistry 38, 2092–2103.

Herrick, J.E., Weltz, M.A., Reeder, J.D., Schuman, G.E., Simanton, J.R., 1999. Rangeland soil erosion and soil quality: role of soil resistance, resilience, and disturbance regime. In: Lal, R. (Ed.), Soil Erosion and Soil Quality. CRC Press, Boca Raton, FL, USA, pp. 209–233.

Herrick, J.E., Jones, T.L., 2002. A dynamic cone penetrometer for measuring soil penetration resistance. Soil Science Society of America Journal 66, 1320–1324.

Johnson, D. C., Ellington, J., Eaton, W. 2012. Institute for Sustainable Agricultural Research, New Mexico State University. Presentation to Sandia National Laboratories, 14 Aug 2012.

Jones, M.B., Donnelly, A., 2004. Carbon sequestration intemperate grassland ecosys- tems and the influence of management, climate and elevated CO_2 . New Phytologist 164, 423–439.

Lal, R., 2008. Sequestration of atmospheric CO_2 in global carbon pools. Energy and Environmental Science 1, 86–100.

Leake, J.R., Johnson, D., Donnelly, D.P., Muckle, G.E., Boddy, L., Read, D.J., 2004. Net- works of power and influence: the role of mycorrhizal mycelium in controlling plant communities and agroecosystem functioning. Canadian Journal of Botany 82, 1016–1045.

Lunt, I., Barlow, T., and Ross, J. 1998. Plains Wandering: Exploring the grassy plains of southeastern Australia. Victorian National Parks Association and the Trust for Nature (Victoria).

Milne, R.M., Haynes, R.J., 2004. Soil organic matter, microbial properties, and aggre- gate stability under annual and perennial pastures. Biology and Fertility of Soils 39, 172–178.

Neary, D.G., Klopatek, C.C., DeBano, L.F., Ffolliott, P.F., 1999. Fire effects on below- ground sustainability: a review and synthesis. Forest Ecology and Management 122, 51–71.

Nicolas V., Oestreicher N., Velot, C. 2016. Multiple effects of a commercial Roundup® formulation on the soil filamentous fungus Aspergillus nidulans at low doses: evidence of an unexpected impact on energetic metabolism. Environ Sci Pollut Res Int. 2016 Apr 11.

Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling organic matter levels in grasslands. Soil Science Society of America Journal 51, 1173–1179.

Pluhar, J.J., Knight, R.W., Heitschmidt, R.K., 1987. Infiltration rates and sediment production as influenced by grazing systems in the Texas rolling plains. Journal of Range Management 40, 240–243.

Presland, G. 1977. Journals of George Augustus Robinson, January-March 1840. Edited with an Introduction. Records of the Victorian Archaeological Survey, No. 5, 2nd Edition.

Rietkerk, M., Ketner, P., Burger, J., Hoorens, B., Olff, H., 2000. Multiscale soil and vegetation patchiness along a gradient of herbivore impact in a semi-arid grazing system in West Africa. Plant Ecology 148, 207–224.

Skinner, R. H. and Dell, C. J. 2016. Yield and Soil Carbon Sequestration in Grazed Pastures Sown with Two or Five Forage Species. Crop Sci. 56:2035–2044 (2016).

Teague, W.R., S.L. Dowhower, S.A. Baker, N. Haile, P.B. DeLaune, D.M. Conover. 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agriculture, Ecosystems and Environment 141 (2011) 310–322.

Teague, W.R., Dowhower, S.L., Baker, S.A., Ansley, R.J., Kreuter, U.P., Conover, D.M., Waggoner, J.A., 2010. Soil and herbaceous plant responses to summer patch burns under continuous and rotational grazing. Agriculture Ecosystems and Environment 137, 113–123.

Thurow, T.L., Blackburn, W.H., Taylor Jr., C.A., 1986. Hydrological characteristics of vegetation types as affected by livestock grazing systems, Edwards Plateau, Texas. Journal of Range Management 39, 505–509.

Thurow, T.L., Blackburn, W.H., Taylor Jr., C.A., 1987. Rainfall interception losses by midgrass, shortgrass, and live oak mottes. Journal of Range Management 40, 455–460.

Thurow, T.L., 1991. Hydrology and Erosion. In: Heitschmidt, R.K., Stuth, J.W. (Eds.), Grazing Management: An Ecological Perspective. Timber Press, Portland, OR, USA, pp. 141–159.

Wright, H.A., Bailey, A.W., 1982. Fire Ecology. John Wiley and Sons, New York.

Yeates, G.W., Bardgett, R.D., Cook, R., Hobbs, P.J., Bowling, P.J., Potter, J.F., 1997. Faunal and microbial diversity in three Welsh grassland soils under conventional and organic management regimes. Journal of Applied Ecology 34, 453–470.