BIOSOLIDS EFFECTS ON VEGETATION AND SOIL OF THE CHIHUAHUAN DESERT

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Introduction
Biosolids are a byproduct of domestic wastewater treatment. The U.S. produced over 8 million tons of biosolids in 1994; annual production was expected to reach 13 million tons by the year 2000. A federal mandate in 1988 prohibited ocean disposal after June 1992. Land-based disposal methods include incineration, landfilling, pelletization, composting, and land application. Because biosolids contain organic matter and a host of macro- and micro-nutrients, land application may be the disposal method of choice: this material can act both as a soil amendment, increasing soil organic matter, and as a fertilizer, increasing forage production and enhancing forage quality via recycling of valuable nutrients.

Southwestern rangelands have received increased attention as suitable ecosystems for land application of biosolids. Wide-open spaces generally remote from congested urban areas, equable climates, and large acreages in private holdings have attracted municipal and commercial sewage disposal entities to pursue the possibilities of increased land application in desert grasslands and shrublands in Texas, New Mexico, and Arizona.

In 1992, we began a long-term research program investigating the effects of topically-applied biosolids on a Chihuahuan desert research site. Our research has concentrated on the desert grassland and desert shrubland communities. We have studied biosolids effects on soil properties, erosion, runoff and infiltration; soil water quality; forage production and forage quality; plant ecophysiological responses; and soil nutrient cycling. Our research has concentrated on the desert grassland and desert shrubland communities.

Research Protocol
A team of range scientists and soil scientists was assembled to develop a coordinated research program that investigated a wide spectrum of issues related to biosolids application. Over the past eight years, six scientists have been involved with research and direction of graduate students toward addressing the issues outlined above.

We have linked our individual research projects together with a relatively standardized methodology that includes application rates of 0, 3, 8, 15, and 40 dry tons/acre to soils of three range sites. State-regulated application rates range from 3 to 8 tons/acre; our highest application rate of 40 tons/acre is intended to document effects of excessive application far above amounts that would ever be applied in a commercial setting. In any research program, it is important to document background responses under controlled (untreated) conditions as well as responses under conditions "beyond the limits". Biosolids applied to research plots were weighed individually and hand-applied to each plot. Chemical constituents and water content were measured for each batch of biosolids applied to research plots.

Research Site
At the beginning of this research project, we completed extensive soil and range site maps of the area prior to biosolids application; additionally, we collected and archived samples of the major soils. The study area, which had been subjected to moderate seasonal grazing by cattle prior to our research, is in mid-fair range condition. Vegetation and soil maps provide detailed documentation of the initial conditions of the study site and will establish a reference point for future comparisons.

Our research site includes about 900 acres of grassland and shrubland in the northern Chihuahuan Desert near Sierra Blanca in Hudspeth County, Texas. Grassland areas on variants of a Loamy range site with loam soils are dominated by tobosagrass and alkali sacaton, with widely scattered mesquite and lotebush; fine sandy loam soils support blue grama, black grama, and assorted dropseeds with yucca and ephedra. Shrubland areas on a gravelly range site are dominated by creosotebush; fluffgrass and assorted dropseeds characterize the typically depauperate herbaceous component of this plant community.

Soils

State and federal regulatory agencies often base biosolids application rates on the balance between nitrogen needs of a plant and "plant available nitrogen" supplied by biosolids. This concept is related to the fact that considerable nitrogen in biosolids can be lost via ammonia volatilization; thus, plant available nitrogen is more important than total nitrogen in establishing application rates that are most beneficial for plant growth. We investigated ammonia volatilization from topically-applied biosolids as it is influenced by seasonal effects representing "hot" (68º to 97º), "intermediate" (43º to 73º), or "cool" (25º to 57º) ambient temperature conditions. Results indicate that 9.5% of the applied NH_3-N is lost via volatilization in the first 3 days following 3-tons/acre application under cool conditions; under hot conditions, 16.6% of the NH_3-N is volatilized within 3 days. Air temperature and its effects on drying potential are especially important in the volatilization process during the first few days following biosolids application: slow drying conditions are more conducive for volatilization to occur over a longer time period than when drying is rapid.

Likewise, degradation of the municipal biosolids is dependent on temperatures. Microbial activity of biosolids exposed to either cold/wet or cold/dry environments decreased to 12% of the maximum activity 1 day after application; declining to no activity by 3-4 days post-application. Microbial activity was higher in hot/wet and hot/dry environments than in either cold/wet or cold/dry environments, but it also decreased rapidly 3 days post-application. Air and soil surface temperatures are important in microbial decomposition of municipal biosolids. Therefore, minimal microbial decomposition occurs after 5-7 days post-application. Preliminary field tests from repeated applications of 3 tons/acre (commercially applied approximately every 15 months) indicate that 80-95% of the organic-C was decomposed from municipal biosolids in nearly 7 years.

A pilot study was conducted of a snapshot in time on the impact of biosolids on the nutrient (NO_3-N and PO_4-P) status of soils from samples taken underneath tobosagrass and biosolids. These samples were compared to the NO_3-N and PO_4-P in the soil at horizontal locations away from the specific point of biosolids application in an effort to evaluate lateral movement as well as vertical movement of macronutrients within a soil profile. These preliminary results indicate that annual application of biosolids (4 consecutive years) increase NO_3-N under the biosolids, especially at 15 and 40 tons/acre, but NO_3-N does not increase in the soil at any distance laterally from the point of biosolids application. The quantity of NO_3-N was least in the surface soil (0 to 2 inches) and greater between 2 and 10 inches. One-time-only application of biosolids has no effect on soil NO_3-N 5 years post-application. Although, repeated annual application of biosolids increases soil NO_3-N, there is no evidence indicating that nitrates move laterally in the soil from the treated areas.

Soil PO_4-P also increased underneath biosolids as the rate of biosolids application increased, but it did not increase in the interstitial areas. In untreated plots, soil PO_4-P averaged about 10 ppm; it increased to about 26 and 40 ppm in plots treated with 15 and 40 tons/acre of biosolids, respectively. Soil PO_4-P was higher in the A horizon than in the B horizon. As with NO_3-N, PO_4-P did not move laterally in the soil from the point of application.

The effect of NO_3-N on tobosagrass from municipal biosolids applied one-time-only was assessed 1 year post-application and into the second growing season. Resident soil NO_3-N in the A horizon of the control plots (0 tons/acre) at the beginning of the growing season (July) was approximately 20 lb/acre. Autumn application of biosolids at 3 tons/acre increased soil NO_3-N in the A horizon to about 50 lb/acre and application of 15 tons/acre increased NO_3-N to about 95 lb/acre at the beginning of the growing season. In October (at the end of the growing season), soil NO_3-N in the A horizon decreased to approximately 9, 12, and 32 lb/acre in the 0, 3, and 15 tons/acre treatments, respectively. Soil NO_3-N in the control and 3 tons/acre treatments were not significantly different. Likewise, soil NO_3-N in the B horizon was relatively high at the beginning of the growing season, but significantly reduced by the end of the growing season. These results suggest that biosolids supply a much-needed source of soil NO_3-N for plant growth. Although, the plants increased in TKN (total Kjeldahl nitrogen), they did not increase in plant NO_3-N. At the end of the growing season, soil NO_3-N content was reduced to approximately the content of resident soil NO_3-N in the control treatments.

Season of biosolids application appears to be important to vegetation response in the first year after biosolids application. This result suggests that timing of nutrient release relative to plant phenology is important. We are studying soil NO_3-N dynamics from spring through the growing season to help explain the importance of season of biosolids application to first year vegetation response. Preliminary results suggest that spring application of biosolids stimulate mineralization of soil organic matter, resulting in high NO_3-N levels at the beginning of the growing season.

Vegetation

In addition to the host of essential plant micro- and macro-nutrients contained in biosolids, the physical presence of biosolids on the soil surface provides a mulching effect that moderates soil surface temperatures and reduces soil water evaporation, both of which are beneficial to plant growth. The effects of nutrient addition and site amelioration, however, are expected to vary depending on rate, season, and frequency of biosolids application. We initiated several studies investigating the combined effects of rate (0 to 40 tons/acre), season (dormant or growing), and frequency (1 year only, or 2, 3, or 4 consecutive years) of biosolids application on tobosagrass and alkali sacaton forage production; these projects also evaluated the effects of supplemental irrigation.

Our results suggest that the influence of season of biosolids application on grass production is important only during the first growing season following application. Standing crops of tobosagrass and alkali sacaton were enhanced more when biosolids were applied during the previous dormant season (early March) than during the growing season (early July). Biosolids applied during the dormant season have positive effects on plants even during the spring prior to the onset of significant summer growth. Tobosagrass and alkali sacaton have the ability to respond to summer-applied biosolids within 3 weeks of a first-time application. Regression analysis indicated that quadratic models are excellent descriptors of a rate (of biosolids application) response that involves a positive linear component, and a negative quadratic component. This suggests that not only is there an upper limit to the increases in grass production that are stimulated by biosolids, but also at the highest rates (40 tons/acre), which are far beyond the level that would ever be commercially applied, there are decreases in production with repeated applications. Standing crop of these species during the second and following growing seasons is not affected by season of application.

In general, although standing crop increases as biosolids application rate increases, it increases at a decreasing rate. Also standing crop usually decreases at the 40-tons/acre rate, especially after multiple applications, relative to lower application rates. However, it is also true that in almost every case we investigated, standing crop in treated plots equaled or exceeded standing crop in untreated plots. We conclude that biosolids generally have a neutral or positive effect on aboveground production of these species.

In addition to once-per-year applications, twice-per-year applications were also tested. Biosolids treatments of 0, 3, 8 and 15 tons/acre were applied to tobosagrass in either winter-summer or spring-summer. During the 4 years of the study (1994-1997), twice-per-year application of biosolids either increased or maintained tobosagrass standing crop. These applications never decreased standing crop when compared to no application of biosolids. Standing crop response was greater for winter-summer application than for spring-summer application only for the first year of the study. Low rates of biosolids (3 and 8 tons/acre) increased tobosagrass standing crop when applied 2, 3, or 4 consecutive years; whereas, 15 tons/acre increased tobosagrass standing crops when biosolids were applied only one or two consecutive years. Standing crop was maintained when 15 tons/acre of biosolids were applied 3 or 4 consecutive years. Supplemental irrigation increased tobosagrass standing crop during the 4 years of the study.

It is commonly thought that the beneficial effects of nutrient addition in desert ecosystems can be realized only if adequate soil water is available. Our research provided the opportunity to test the "water-limited, nutrient-regulated" hypothesis. If this hypothesis is true, then we would expect an interaction between biosolids application and supplemental irrigation. In general, our results do not support this hypothesis: whereas, the effects of supplemental irrigation were always significant, they seldom interacted with the effects of biosolids on plant growth. In general, the effects of additional water and additional nitrogen act independently in influencing standing crop of tobosagrass and alkali sacaton.

Although increasing forage production with biosolids is an important benefit to a producer, it is equally important that the nutrient quality of the forage is enhanced by biosolids. We have investigated forage quality of tobosagrass as it is affected by biosolids application. After a one-time-only autumn application of biosolids, we detected increases in plant-TKN, Mg, Mn, and Na; these effects generally carried over into the second growing season. Additionally, for elements that showed increases as a result of biosolids application, none were increased to levels considered excessive or toxic according to the CRC Handbook of Trace Elements in Plants and Soils. Therefore, we conclude that biosolids not only increase forage production, but also improve forage quality.

Since municipal biosolids are organic in nature, they have the potential to influence plant growth by physically altering the microenvironment or chemically through the release of macro- and micro-nutrients as well as trace elements. Therefore, a study was designed to compare blue grama response (growing on an Armesa soil) to biosolids and to chemical fertilizers (urea or monoammonium phosphate, MAP). Biosolids were applied one-time-only at the outset of the study at 0, 3, 8, and 15 tons/acre. Urea and MAP were applied annually at rates equivalent to plant available nitrogen and phosphorus, respectively, provided by the biosolids over the 3-year study. Urea did not increase standing crop of blue grama over the control. Biosolids enhanced blue grama productivity through physical and chemical effects, but MAP produced more blue grama biomass at rates of P provided by 15 tons/acre of biosolids. Therefore, in general, biosolids provide dual benefits (chemical and physical) to desert rangelands compared to synthetic chemical fertilizers.

Measurements of standing crop are production-oriented indices of plant response to biosolids. We have also studied plant physiological responses to biosolids in an effort to better understand the production responses we have documented. In these studies, we have investigated how biosolids affect leaf area, photosynthesis, and water use efficiency of tobosagrass, blue grama, and creosotebush.

Leaf area production is greatly increased by biosolids application in blue grama and tobosagrass. Development of leaf area is much more sensitive to the application of biosolids than photosynthesis rates at the single-leaf level. This is probably due to the fact that these species possess the C_4 photosynthetic pathway, which makes them highly efficient in CO_2 fixation, and apparently they may be naturally more limited by nutrient supply. Due to the increase in leaf area, photosynthesis at the canopy level increases as biosolids rates increase. Water use efficiency is higher in plants treated with biosolids, especially when water is in short supply. Biosolids provide abundant nitrogen to the rooting medium, which leads to the increase in leaf area and supports more efficient metabolism in both grasses.

Rooting behavior of creosotebush, which is typically considered a deep-rooted shrub, indicates that 80% of the roots are in the upper portion of the soil profile (upper 50 cm). Creosotebush has the unique ability to respond quickly to light rains. The apparent mulching effect of biosolids (15 and 40 tons/acre) provided adequate soil moisture for photosynthesis to occur during dry periods of the year. During the rainy season, creosotebush photosynthesis was highest in biosolids regimes treated with 3 and 8 tons/acre. Branch growth and leaf area were increased by biosolids applied at a rate of 8 tons/acre, primarily through increased soil water via mulching by the biosolids. In general, photosynthesis, water relations, growth and development in creosotebush are influenced by biosolids.

Since topically-applied biosolids can moderate soil temperature extremes and reduce soil water evaporation, measurements were made to evaluate these microenvironmental modifications on seedling emergence and survival. Topically-applied biosolids ameliorate the microenvironmental conditions and enhance the opportunities for seedling emergence. These effects are expected to be more evident under limiting soil water conditions. However, once seedlings have emerged, root growth under biosolids is less than it is where biosolids have not been applied, which might be attributed to increased root growth of seedlings under relatively limiting soil nutrient conditions.

Results from the vegetation studies clearly show that it is ecologically naïve and environmentally irresponsible to ignore the many interactions that can occur involving effects of rate of application, season of application, number of consecutive years of application, irrigation effects, species involved, and of course, the general environmental conditions that plants experience during the particular growing season in question. All of these factors must be considered when evaluating biosolids effects in Desert Grasslands. As the ecologist Robert May wrote, "ecology is the science of contingent generalization"; in other words, "it depends" in this ecological arena, where the "it" involves responses to biosolids, and the "depends" calls on the many environmental factors that also influence plant growth in addition to the biosolids effects.

Hydrology

Biosolids application in arid and semiarid ecosystems can be expected to have important impacts on hydrological processes that are significant both at a small scale and at a large scale. Indeed, to the extent that erosion, runoff, and infiltration are affected on a particular square foot of rangeland that has been treated with biosolids, we can expect major hydrological consequences on the scale of 1,000-acre land units that are treated in commercial application projects. Thus, it is important to understand how biosolids affect the basic processes of soil water infiltration, runoff, and erosion.

We used a portable rainfall simulator to study how infiltration and runoff are affected by biosolids. The simulator applied water at a rate of 6.4 inches/hour for a 30-minute period to plots treated with 0, 3, 8, 15, or 40 dry tons/acre of biosolids on a Loamy range site dominated by tobosagrass and a Gravelly range site characterized by creosotebush. On the Loamy range site, we also studied the effects of biosolids applied on top of tobosagrass plants and in bare areas between plants.

Application of biosolids to the soil surface reduces soil erosion. For example, in the bare areas between tobosagrass plants, even the lowest biosolids rate (3 tons/acre) reduced erosion by about 40% compared to bare areas not treated with biosolids. Infiltration is increased as biosolids rates increase up to and including 40 tons/acre. Concomitantly, soil erosion is decreased as biosolids rates increase. Although interception by biosolids is small (depending on amount of time lapse between the precipitation event and biosolids application) interception loss increased as biosolids rates increased. Consequently, biosolids affect important hydrologic parameters.

These effects are consequences of at least two factors. Topically-applied biosolids provide a surface cover that can absorb the impact of falling raindrops, thereby reducing the detachment of soil particles that occurs during storm events. Additionally, biosolids increase soil organic carbon, particularly at the soil surface, which inhibits crust formation and thus increases infiltration. The net result of biosolids application is reduced soil erosion and runoff, and increased soil water infiltration.

Water Quality

Soil water quality issues associated with biosolids application relate to quality of water that infiltrates into a treated soil, and to quality of water that runs off a treated soil. Our research has investigated both of these concerns.

We used microlysimeters constructed of 10-inch polyvinyl chloride well casing to study quality of water that has passed through soils treated with biosolids. Lysimeters were inserted into a loam soil dominated by tobosagrass and a fine sandy loam soil dominated by black grama, extracted with a soil column intact, and transported to an on-site indoor laboratory for future study. In the first phase of this study, biosolids were topically-applied to the surface of the soil. Water was hand-sprinkled to simulate rainfall until sufficient leachate was collected from the bottom of the lysimeter for chemical analyses. A Hach Kit (DL-ER-4) was used to analyze leachate for Cl^{-}, NO_3-N, pH, orthophosphates, SO_4^{-2}, Ca-hardness, and total hardness. Inductively Coupled Plasma (ICP) procedures were used to analyze for 20 elements including Al, Be, Cd, Cu, Fe, Pb, and Mo.

In general, when biosolids affected soil water constituents, the effects were associated with the highest application rate of 40 tons/acre. In fact, our measured chemical constituents indicated that leachate was generally within EPA drinking water standards for biosolids application rates up to and including 15 tons of biosolids/acre. Thus, soil water quality associated with topical application of biosolids should not be a concern.

However, when we repeated this investigation with biosolids that were incorporated into the top 4 inches of the soil in the lysimeters, we found markedly different results. For example, incorporation clearly increased the release of mobile constituents such as NO_3-N, SO_4^{-2}, and Cl^-. Nitrate-nitrogen was never below drinking water standards even in untreated lysimeters, indicating that soil water quality may be affected by soil disturbance, even in the absence of biosolids, as well as by biosolids. Therefore, our results suggest that water quality of leachate is well within the range of drinking water standards when biosolids are topically-applied at commercially regulated rates.

We also studied the quality of runoff water from biosolids-treated soils. The EPA has established maximum contaminant levels (MCLs) for health-related trace contaminants in drinking water. A trace contaminant is defined as an element or compound with a standard tolerance level allowed which is generally less than 1 ppm. Secondary maximum contaminant levels (SMCLs) that affect aesthetic quality of drinking water have also been established. SMCLs are not related to health issues.

Our results indicate that all of the trace elements and compounds for which an MCL has been established were below the MCL. Likewise, those elements and compounds for which a SMCL has been established were well below the SMCL except for Mn. We conclude that runoff water generally meets EPA standards for drinking water at all application rates except 40 tons/acre.

Conclusions
Municipalities nation-wide are producing increasing amounts of biosolids. Although at the site of production biosolids may be considered a waste, it should also be appreciated that because of their high organic matter and nutrient content, biosolids can be considered a valuable natural resource which, if not recycled, will indeed be wasted. "Beneficial use" application, a regulatory term of the EPA, may also be accurate in an ecological sense. When biosolids that are free from excessive trace elements and pathogens are topically applied to arid and semiarid rangelands in accordance with responsible regulation and on-site management, our results show that a suite of consequences follows, including:

- reduced soil erosion and soil water runoff,
- increased soil water infiltration,
- acceptable soil water quality,
- enhanced plant water use efficiency,
- increased forage production, and
- improved forage quality.

Although range managers and land applicators may have operation-specific management goals and objectives, from most perspectives these effects of biosolids application represent overall rangeland improvement.