The potential of soil amendments for restoring severely disturbed grasslands

Brian M. Ohsowski[a], John N. Klironomos[a], Kari E. Dunfield[b], Miranda M. Hart[a,*]

[a] Department of Biology, University of British Columbia, Okanagan, Kelowna, BC, Canada V1V 1V7
[b] Department of Land Resource Science, University of Guelph, Guelph, ON, Canada N1G 2W1

ARTICLE INFO

ABSTRACT

Habitat destruction and land use change are among the anthropogenic influences affecting many ecosystems. After environmental degradation, restoration and reclamation efforts can be hampered by poor physio-chemical soil characteristics and reduced soil community complexity. To enhance degraded system recovery, soil manipulations may be necessary to alleviate habitat destruction. This review will (1) discuss grassland restoration in terms of ecosystem-level processes, and (2) analyze the efficacy of novel and easily applicable amendments (i.e. compost, biochar, and arbuscular mycorrhizal fungi) to facilitate grassland recovery in severely degraded habitats. We suggest that restoration practitioners emphasize soil ecological knowledge and microbial processes in tandem with native plants when restoring damaged ecosystems. This review is intended to guide practitioners in the promotion of grassland ecosystem sustainability.

1. Introduction

Human-induced disturbance is pervasive among all ecosystems as the result of waste accumulation, industrial pollution, resource extraction, and urban sprawl (Hannah et al., 1995). Previous land use, ranging from industrial spoils (e.g. mine tailings, contaminated brownfields) to road construction, dictates the approach of a restoration project (Jackson and Hobbs, 2009). For our purposes, we define a severely disturbed landscape as an area manipulated in such a way that the pre-existing habitat can no longer be maintained. In this review, we will focus on the restoration of grassland vegetation and ecosystem processes in degraded habitats.

The definition of restoration success is largely dependent upon the goals of the restoration practitioner. Goals can range from achieving diversity indices (e.g. organism richness and abundance), vegetative structure (e.g. percent cover, biomass, vegetative profiles), or ecosystem process reestablishment (e.g. nutrient cycling and soil stabilization) (Ruiz-Jaen and Aide, 2005). The current paradigm in restoration tends to be phytocentric while underemphasizing belowground food webs (van der Heijden et al., 2008; Kardol and Wardle, 2010) and soil ecological knowledge (Callaham et al., 2008). Furthermore, restoration projects tend to evaluate short-term outcomes for vegetative and microbial production, as well as soil processes.

Practitioners need viable techniques that influence the recovery of the entire ecosystem. After severe disturbance (i.e. post-mine areas), edaphic conditions and soil communities may not support diverse plant communities. The addition of inoculum and soil conditioners can address some components of the soil environment. Soil amendments should create more suitable conditions for diverse and productive plant communities. With an ecosystem-level approach to restoration, native plant production is the consequence of the restoration practice, not the focus.

2. Landscape restoration and successional theory

Historically, ecological succession has been viewed in terms of stable, climax community endpoints (Clements, 1916; Odum, 1969). Current thought recognizes that community diversity is shaped by environmental fluctuations at large spatial, temporal, and organizational scales (Pimm, 1991). Successional pathways can be multi-directional, driven by stochastic processes and disturbance, thus long-term community stability will never be maintained (Glenn-Lewin and van der Maarel, 1992). This implies that an ecosystem has multiple, alternative stable states separated by unstable transitions (Scheffer et al., 2001). Alternative stable states depend upon the surrounding biotic community, order of organism arrival, and inherent system randomness. In terms of restoration, degraded systems are often in a persistent stable state (Suding et al., 2004). Plant establishment and soil building in degraded habitats may be slow to recover by natural successional processes without human intervention.

Restoration ecology and successional theory often address similar questions, albeit from different perspectives. Successional pathways are comprised of temporal changes in community assembly, biodiversity, and biogeochemical cycles (Walker et al.,

2007). Habitat restoration manipulates these processes to accelerate target community establishment (Harris, 2009). Successional research, generally confined to one ecosystem, addresses time scales related to vascular plant life history (10–200 years). In contrast, landscape restoration operates on broad spatial scales (e.g. altitude gradients, moisture gradients, catchment basins) (del Moral et al., 2007), focusing on the duration of human involvement (1–20 years).

A practical application of successional mechanisms in restoration has not been broadly developed for practitioners (Walker et al., 2007). Restoration ecologists must acknowledge the potentially persistent stable state of degraded systems. Feedback mechanisms between biotic and abiotic factors in degraded systems may suppress plant establishment and community sustainability. For example, Ash et al. (1994) described abandoned waste areas in northwest England that had reduced plant cover and diversity after a century following disturbance.

2.1. Post-mine areas as primary succession models

Abandoned mine lands (e.g. ore extraction, gravel pits) are analogous to natural primary succession events such as volcanic activity or glacial retreat. The extraction process completely removes flora, fauna, and soils of the previous system. Following resource exhaustion, post-mine areas are typically characterized by low soil organic matter (SOM) content, low fertility, and poor physio-chemical and biological properties (Bradshaw, 2000). The resulting raw substrate (i.e. subsoils and rock material) is a stark contrast to the abiotic and biotic soil complexity of the original habitat. As a consequence, natural reestablishment of above- and belowground communities in abandoned mine areas is typically slow (Bradshaw, 1997).

Suppressed regeneration of biotic communities may be due to reduced biological complexity in post-mine substrates. The deposition and subsequent heterotrophic turnover of organic matter is a critical link for facilitating plant establishment. Restoration projects in degraded soils must include attempts to rehabilitate, at least in part, biological complexity. Biological colonization requires a source of energy and nutrients, which may be initially lacking in post-mine substrates (Frenot et al., 1998). One solution is to add organic detritus containing natural microbial assemblages (e.g. bacteria (Tscherko et al., 2003; Bardgett et al., 2007), cyanobacteria (Nemergut et al., 2007), and fungi (Hodkinson et al., 2002)). These microbes actively turn over organic substrates and prime biogeochemical cycles.

3. An ecological context of degraded system restoration

Clearly, soil health is paramount to restoration success in devastated landscapes. Soil microbial communities play a major role in the development and sustainability of soil health (Anderson, 2003). Soil health is defined as the capacity of soil to function as a living system, sustaining biotic productivity, and maintaining ecosystem services (Doran and Zeiss, 2000). Soil microbial communities are well correlated with *plant primary production* (Bardgett and Wardle, 2003; van der Heijden et al., 2008; Heneghan et al., 2008; Benayas et al., 2009) and integral in the *recycling of organic matter and nutrients* (Wardle et al., 2002). Decomposers (Harte and Kinzig, 1993; Reynolds et al., 2003), mycorrhizal fungi (Klironomos, 2002) and nitrogen-fixing bacteria (van der Heijden et al., 2008) are key soil functional groups in the rhizosphere (i.e. soil area directly influenced by plant tissues and secretions). Soil microbial communities are also important for *soil stabilization* via stabile aggregate formation (Rillig, 2004; Six et al., 2004). These factors can ultimately mediate successional dynamics and plant community composition (Wardle et al., 2004), thus contributing to the reestablishment of natural systems in severely disturbed landscapes.

Edaphic characteristics, resource availability, and soil microorganisms mediate aboveground biotic responses to include primary productivity (Baer et al., 2004), organic matter decomposition rates (Smith and Bradford, 2003), and plant community structure (Baer et al., 2003; Heneghan et al., 2008). CENTURY (Parton et al., 1993) is an established ecosystem-level model of plant–soil biogeochemical cycles, models the links among plant productivity, decomposition, climate and land management options. Among its many functions, CENTURY emphasizes the role of carbon management decisions under natural and agricultural scenarios. Restoration projects that appropriately manage soil organic matter dynamics and soil microbial feedbacks may increase production and carbon storage in disturbed habitats (Ojima et al., 1993). Practitioners should emphasize soil carbon cycles and microbial processes in tandem with plant establishment in damaged ecosystems (Cairns, 2000).

4. Grassland vegetation

Grassland productivity varies with habitat classification, ranging from shortgrass steppe (least productive) to tallgrass prairies (most productive) (Knapp and Smith, 2001). Grassland productivity is ultimately dictated by the availability of three limiting resources: light, water, and nitrogen (Baer et al., 2003). Resource availability is determined by patterns in precipitation (Sala et al., 1988), soil characteristics (Briggs and Knapp, 1995), herbivory (Knapp et al., 1999), and periodic fires (Knapp and Seastedt, 1986). Plant production in grasslands will ultimately depend upon adaptations to spatial and temporal availabilities of these limiting resources.

Grassland restoration in severely degraded habitats must recognize the factors that shape and maintain these communities. Grassland plants are evolutionarily adapted to the mentioned environmental context. Restoration projects incorporating locally adapted plant populations are more likely improve rates of establishment and persistence (Pywell et al., 2002). Resulting plant communities are expected to more closely resemble natural grassland remnants and encourage the conservation of rare flora and fauna.

Four functional groups composed of herbaceous perennials dominate grassland communities: perennial C4 grasses, C3 graminoids (grasses and sedges), nitrogen-fixing species (primarily Fabaceae), and late summer flowering, drought-hardy composites (Asteraceae) (Kindscher and Wells, 1995). Cool season C3 grasses have traits that provide early season plant cover, nutrient-rich plant tissues beneficial to herbivores, and have decreased light requirements ideal for shady refugia. Compared to cool season grasses, warm season C4 grasses exhibit higher water-use efficiency, higher plant biomass potential, late season growth, and tolerance of full sun exposure (Tieszen et al., 1997). Composite forbs are integral in rapidly colonizing open soil (especially after grazing or fire disturbances), supporting pollinator populations, and driving overall plant community diversity indices (Pokorny et al., 2004). Forbs in the legume family (Fabaceae) form a symbiotic relationship with nitrogen-fixing bacteria. Nitrogen-fixing bacteria are found within legume root nodules, and convert biologically unavailable atmospheric N_2 gas into forms of nitrogen useable by plants. In exchange for usable nitrogen, the plant delivers a supply of nutrition in the form of carbohydrates. Nitrogen-rich legumes within grasslands can contribute to the total nitrogen pool of soils during growth and after senescence (Oelmann et al., 2007). Soil nitrate and ammonium levels are usually limited within grasslands due to rapid utilization and immobilization by primary producers and microbial decomposers (Risser and Parton, 1982). The introduction of N-fixing plants may affect the structure and function of grassland systems.

Restoration projects that incorporate multiple functional groups and high numbers of species are more likely to achieve community sustainability (Piper and Pimm, 2002). Long-term ecosystem

stability depends on communities containing species or functional groups that are capable of differential response to disturbance (McCann, 2000; Hooper et al., 2005). Studies of grassland ecosystems indicate that increased diversity can be expected, on average, to give rise to resistance and resilience (Tilman et al., 1997; Tilman and Downing, 1994). Higher species diversity may also lead to increased plant production due to species complementarity (Cardinale et al., 2007). Restoration projects that maintain high species diversity with varied functional traits could increase the likelihood of achieving long-term community stability.

5. Techniques for improving disturbed soils in grassland restoration projects

The positive effects of soil amendments on plant and microbial production within agricultural systems, restoration projects, and greenhouse experiments have been extensively recognized. In the following section, we review three typical amendments that are widely accessible to restoration practitioners. These amendments (i.e. biochar, compost, arbuscular mycorrhizae) have had promising results both in greenhouse and field settings.

5.1. Vegetation-derived biochar

Application of black carbon to soils is expected to build soil organic matter, enhance nutrient biogeochemical cycles, lower bulk soil density, increase bioavailable water, and reduce nutrient leaching (Shrestha et al., 2010). Black carbon consists of all C-rich residues, ranging from partly charred material to graphite and soot particles, resulting from the incomplete combustion of organic materials (Schmidt and Noack, 2000). Research has shown that prairie soils contain substantial amounts of black carbon resulting from a 10,000 year legacy of prairie fires (Skjemstad et al., 2002; Brodowski et al., 2005). Laird (2008) estimates that between 5 and 15% of the total organic carbon in natural Midwestern prairie soils is composed of black carbon. Within boreal forests, short-term soil fertility effects have been attributed to increased charcoal fractions in the soil after naturally occurring fires (Wardle et al., 1998).

Historically, human agricultural practices (i.e. terra preta soils in the central Amazon) have long recognized plant growth benefits of black carbon soil supplements (Glaser et al., 2002). Terra preta literally translates to "black earth" in Portuguese. These ancient soils (500–7000 YBP) have been anthropogenically amended with black carbon, bones, and manure. Compared to adjacent infertile soils (terra comum or "common soils"), the concentration of black carbon in terra preta soils is seventy times greater. Furthermore, these soils still exhibit three times more soil organic matter, nitrogen, and phosphorus in comparison to neighboring terra comum soils (Glaser, 2007).

One form of refined black carbon being used in environmental management is biochar, or carbon-rich charcoal (Lehmann and Joesph, 2009). To create biochar, organic materials (i.e. feedstocks) are heated to temperatures between $300\,°C$ and $800\,°C$ in a low oxygen environment. Anoxic conditions during heating leads to the incomplete combustion of the organic matter, thus producing biochar. Feedstocks may include agricultural wastes, forestry wastes, wood pellets, or manures. The high temperatures used in pyrolysis induce molecule polymerization within feedstocks to produce aromatic and aliphatic compounds (Sohi et al., 2009). This creates a stable product demonstrated to be a potential sink for atmospheric CO_2 and beneficial soil amendment (Lehmann and Rondon, 2006; Lehmann, 2007). When incorporated into soils, initial degradation of biochar by chemical oxidation and microbial processes has been noted (Bruun et al., 2008; Nguyen et al., 2008; Smith et al., 2010). The recalcitrant properties of black carbon

stocks eventually stabilize and resist microbial degradation within soils for 100–1000+ years (Glaser et al., 2002).

Amended soils benefit from biochar's large, oxidized surface area and porous structure. Soils amended with biochar have an increased soil charge density (potential cation exchange capacity [CEC] per unit surface area) in comparison to non-amended soils (Liang et al., 2006). Biochar improves: (1) soil nutrient availability and retention (i.e. major cations, phosphorus, total nitrogen) (Lehmann et al., 2003), (2) acidic soil pH (Novak et al., 2009), (3) organic matter adsorption (Shrestha et al., 2010), and (4) soil aeration (Shrestha et al., 2010).

Biochar as a soil amendment has generated promising results within agricultural systems and greenhouse experiments. Recent research has demonstrated that biochar amended soils have greater crop biomass (Rondon et al., 2004; Major et al., 2010) and enhanced biological N-fixation in leguminous crops (Rondon et al., 2007). The fertilizer effect induced in plants may be explained by the retention of beneficial nutrients and pH neutralization.

Indirectly, plant growth may be stimulated by increased mycorrhizal associations (Nishio and Okano, 1991; Ishii and Kadoya, 1994) and soil microorganism activity (Thies and Rillig, 2009). Warnock et al. (2007) proposed four mechanisms that may benefit arbuscular mycorrhizal fungi in soils with biochar: (1) positively changing physio-chemical soil properties (i.e. CEC, bioavailability of phosphate [PO_4^-] in low P soils), (2) promoting beneficial soil organisms (i.e. phosphate solubilizing bacteria, mycorrhization helper bacteria), (3) adsorbing plant secretions that may alter mycorrhizal root colonization, and (4) providing a grazing refuge in biochar's porous structure. In general, increased soil microbial activity in biochar amended soils may also be attributed these hypothesized mechanisms for AMF.

Biochar soil amelioration in severely degraded landscapes has the potential to increase grassland plant production, enrich soil microbial populations, and stimulate arbuscular mycorrhizal persistence. Biochar is hypothesized to reduce nutrient leaching in well drained soils. Nutrient retention in impoverished post-mine substrates should increase productivity by stimulating biotic–abiotic feedbacks.

5.2. Leaf and yard waste (LYW) compost

Agricultural societies have historically recognized that ameliorating fields with compost results in improved soil conditions. Soil disturbance (e.g. mining or tillage) generally decreases SOM pools due to erosion and disruption of the biogeochemical mechanisms and microbial communities associated with SOM pools (McLauchlan, 2006). When added to soils, composted material increases soil fertility by increasing: (1) soil organic carbon (Crecchio et al., 2004; Walter et al., 2006), (2) available soil nitrogen (Eriksen et al., 1999; Gabrielle et al., 2005), phosphorus (Wortmann and Walters, 2007), and micronutrients (i.e. iron, copper, zinc) (Hargreaves et al., 2008), (3) water holding capacity (Movahedi-Naeini and Cook, 2000), (4) cation exchange capacity (McConnell et al., 1994), (5) soil aggregation (Bresson et al., 2001; Annabi et al., 2007; Abiven et al., 2009), and (6) neutralization of acid soils (Mkhabela and Warman, 2005).

Leaf and yard waste (LYW), largely composed of community organic waste, is typically composted at large scales. During aerobic LYW composting, theromphilic microbes assimilate and mineralize complex organic compounds while releasing heat, water vapor, CO_2, and ammonia waste products. The remaining non-mineralized organic material is humified to form the stable end product, compost. Civic and environmental benefits of composting LYW include waste volume reduction, microbial pathogen and weed sterilization (due to high temperatures), and odor suppression (Jakobsen, 1995). LYW compost derived from municipal processing facilities is

utilized in gardens, organic agriculture, land reclamation, and slope stabilization projects.

Research demonstrates direct increases to crop biomass (Montemurro et al., 2006) and nutritional quality (Allievi et al., 1993) in compost amended soils. Compost addition strongly influences soil microbial communities by increasing microbial biomass, respiration rates, and soil enzyme activity (Albiach et al., 2001). As bacterial and fungal decomposers utilize and sequester carbon in amended soils, concentrations of total nitrogen and phosphorus increase over time (Iglesias-Jiménez, 2001; Wolkowski, 2003). Long-term ramifications of microbial community activity (Ros et al., 2006) and soil biochemical characteristics (García-Gil et al., 2004) due to compost ameliorations have been noted. Pascual et al. (1999) found microbial biomass, soil basal respiration, and dehydrogenase activity near natural soil levels eight years after a single compost amendment to semi-arid, Mediterranean soils. Within restoration projects specifically, compost bolstered arbuscular mycorrhizae inoculum persistence, thus benefiting native plant cover (Noyd et al., 1996; Celik et al., 2004). In semi-arid soil restorations, extensive work from Caravaca et al. suggest short-term (Caravaca et al., 2002a,b, 2003a) and medium-term (Caravaca et al., 2003b) influences of mycorrhizal inoculations and compost ameliorations. Sharp increases in plant primary production were attributed to the abiotic–biotic link between bioavailable phosphorus supplied by compost residues and AMF phosphorus uptake.

In sandy soils with low SOM, compost improves soil structure (Wahba and Darwish, 2008), bioavailable nutrients (P, K, Mg) (Weber et al., 2007), total inorganic N (Busby et al., 2007), plant production (Mkhabela and Warman, 2005), and soil microbial activity (Ros et al., 2006). Low SOM and poor physio-chemical properties in post-mine substrates are expected to have restricted microbial community activity and depleted nutrients. LYW compost amendments should increase microbial activity (Ros et al., 2003), mycorrhizal persistence (Gaur and Adholeya, 2005), and increase plant biomass. To date, few studies have researched the effect of compost application to native plants and mycorrhizal communities in severely degraded post-mine substrates (Busby et al., 2007).

5.3. Arbuscular mycorrhizal fungal inoculation of grassland plants

Arbuscular mycorrhizal fungi (AMF) are globally distributed soil microorganisms that form symbiotic associations with more than 80% of terrestrial plants (Smith and Read, 2008). These obligate biotrophs constitute a major fraction of the plant-associated soil microbial community. In exchange for host plant-derived photosynthate, arbuscular mycorrhizae benefit plants by: (1) increasing soil nutrient acquisition and subsequent assimilation into plant tissues (especially phosphorus), (2) protecting target plant roots from pathogens, (3) enhancing seedling performance, (4) improving plant water relations, and (5) improving soil stabilization. In addition to improved target plant performance, AMF communities directly relate to the biodiversity of plant communities (van der Heijden et al., 1998).

Positive plant growth responses to mycorrhizae have stimulated the emergence of biotech companies promoting the use of commercially-produced AMF inoculum as a soil enhancement agent. In horticultural systems (Azcón-Aguilar and Barea, 1997) and landscape restoration (Miller and Jastrow, 1992), mycorrhizal inoculum has been recommended to increase plant growth performance. The intentional movement of mycorrhizal fungal species is growing, but the potential negative ecological ramifications of non-native arbuscular mycorrhizal invasion are poorly understood (Schwartz et al., 2006). Evidence indicates that symbiotic associations between plants and fungus range from parasitic to beneficial depending on host plant/AMF pairings (Klironomos, 2003). Depending on the biogeochemical context and AMF–plant associations within an ecosystem, AMF inoculation may yield positive, neutral, or negative plant growth effects in the field. Furthermore, a recent greenhouse study by (Mummey et al., 2009) indicated that plant pre-inoculation with AMF may have unintended implications for resident AMF communities. AMF inoculum may restrict assembly potentials in resident soil AMF communities with divergent phylogenies, thus suppressing plant growth and foliar nutrients. As research indicates AMF phylogeny diversity in host plant roots directly correlates to increased plant growth responses (Maherali and Klironomos, 2007), restricting native soil inoculum potentials could have ramifications to plant production and soil feedback mechanisms in a restoration project.

The ramifications of pre-inoculating native plants with AMF inoculum in severely degraded habitats have not been thoroughly addressed. Evidence indicates that after major soil disturbances such as agricultural tilling, native AMF associations are fractured and strongly diminished (Jansa et al., 2002, 2003). The resident AMF community in post-mine substrates is expected to be strongly reduced compared to natural grassland soils. To date, the resident AMF community soil inoculum potential within post-mine substrates has not yet been identified. The AMF inocula potential in severely disturbed sites should be determined by spore immigration rates, soil nutrient availability (i.e. phosphorus availability), plant identity (i.e. obligate mycorrhizal plants vs. facultative mycorrhizal plants vs. non-mycorrhizal plants) in the degraded area, and time since landscape disturbance (Allen and Allen, 1980).

To date, some AMF inoculation research has been conducted in non-toxic post-mine reclamation areas. These field studies indicate that AMF benefit native plant production and establishment in severely degraded areas (Johnson, 1998; Matias et al., 2009). Mycorrhizal inoculum is anticipated to benefit plant production in post-mine substrates due to a lack of an existing AMF community.

6. Conclusions

It is imperative that restoration practitioners integrate soil ecological knowledge into the reclamation of degraded habitats. Emphasizing an ecosystem-level approach to grassland restoration in degraded areas should increase landscape recovery time and reduce plant failure. When used in combination, the addition of mycorrhizal fungi, biochar, and compost approaches the goal of a viable soil environment for sustainable plant growth.

It is clear that soil amendments are a necessary to restore severely disturbed landscapes in a reasonable timeframe. A checklist or key could be developed to facilitate identification of factors that are important for determining the most appropriate amendments and practices. Application rates of biochar and compost could be determined experimentally to establish a feasible restoration protocol under a variety of restoration scenarios. Since universal application of soil microorganisms may not always be beneficial, more studies testing the use of locally bolstered inoculum sources should be conducted to eliminate the environmental impact of foreign inocula.

The list of amendments discussed is by no means complete. Other amendments may include inoculation (e.g. nitrogen-fixing bacteria, earthworms), and organic materials (e.g. biosolids, hydrogels, paper mill sludge). Further research into the integration of these amendments into severely degraded landscapes during restoration projects needs to be conducted. As we make advancements in biotechnology and soil conditioners, we can reduce

long-term maintenance costs and create a foundation for sustainable above- and belowground communities.

References

Abiven, S., Menasseri, S., Chenu, C., 2009. The effects of organic inputs over time on soil aggregate stability – a literature analysis. Soil Biol. Biochem. 41, 1–12.

Albiach, R., Canet, R., Pomares, F., Ingelmo, F., 2001. Organic matter components and aggregate stability after the application of different amendments to a horticultural soil. Bioresour. Technol. 76, 125–129.

Allen, E.B., Allen, M.F., 1980. Natural re-establishment of vesicular–arbuscular mycorrhizae following stripmine reclamation in Wyoming. J. Appl. Ecol. 17, 139–147.

Allievi, L., Marchesini, A., Salardi, C., Piano, V., Ferrari, A., 1993. Plant quality and soil residual fertility six years after a compost treatment. Bioresour. Technol. 43, 85–89.

Anderson, T., 2003. Microbial eco-physiological indicators to asses soil quality. Agr. Ecosyst. Environ. 98, 285–293.

Annabi, M., Houot, S., Francou, C., Poitrenaud, M., Bissonnais, Y.L., 2007. Soil aggregate stability improvement with urban composts of different maturities. Soil Sci. Am. J. 71, 413–423.

Ash, H.J., Gemmell, R.P., Bradshaw, A.D., 1994. The introduction of native plant species on industrial waste heaps: a test of immigration and other factors affecting primary succession. J. Appl. Ecol. 31, 74–84.

Azcón-Aguilar, C., Barea, J.M., 1997. Applying mycorrhiza biotechnology to horticulture: significance and potentials. Sci. Hortic. 68, 1–24.

Baer, S., Blair, J., Collins, S., Knapp, A., 2004. Plant community responses to resource availability and heterogeneity during restoration. Oecologia 139, 617–629.

Baer, S.G., Blair, J.M., Collins, S.L., Knapp, A.K., 2003. Soil resources regulate productivity and diversity in newly established tallgrass prairie. Ecology 84, 724–735.

Bardgett, R.D., Wardle, D.A., 2003. Herbivore-mediated linkages between aboveground and belowground communities. Ecology 84, 2258–2268.

Bardgett, R.D., Richter, A., Bol, R., Garnett, M.H., Bäumler, R., Xu, X., Lopez-Capel, E., Manning, D.A.C., Hobbs, P.J., Hartley, I.R., Wanek, W., 2007. Heterotrophic microbial communities use ancient carbon following glacial retreat. Biol. Lett. 3, 487–490.

Benayas, J.M.R., Newton, A.C., Diaz, A., Bullock, J.M., 2009. Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. Science 325, 1121.

Bradshaw, A., 1997. Restoration of mined lands – using natural processes. Ecol. Eng. 8, 255–269.

Bradshaw, A., 2000. The use of natural processes in reclamation – advantages and difficulties. Landscape Urban Plan. 51, 89–100.

Bresson, L.M., Koch, C., Le Bissonnais, Y., Barriuso, E., Lecomte, V., 2001. Soil surface structure stabilization by municipal waste compost application. Soil Sci. Am. J. 65, 1804–1811.

Briggs, J.M., Knapp, A.K., 1995. Interannual variability in primary production in tallgrass prairie: climate, soil moisture, topographic position, and fire as determinants of aboveground biomass. Am. J. Bot. 82, 1024–1030.

Brodowski, S., Rodionov, A., Haumaier, L., Glaser, B., Amelung, W., 2005. Revised black carbon assessment using benzene polycarboxylic acids. Org. Geochem. 36, 1299–1310.

Bruun, S., Jensen, E.S., Jensen, L.S., 2008. Microbial mineralization and assimilation of black carbon: dependency on degree of thermal alteration. Org. Geochem. 39, 839–845.

Busby, R.R., Allen Torbert, H., Gebhart, D.L., 2007. Carbon and nitrogen mineralization of non-composted and composted municipal solid waste in sandy soils. Soil Biol. Biochem. 39, 1277–1283.

Cairns, J., 2000. Setting ecological restoration goals for technical feasibility and scientific validity. Ecol. Eng. 15, 171–180.

Callaham Jr., M.A., Rhoades, C.C., Heneghan, L., 2008. A striking profile: soil ecological knowledge in restoration management and science. Restor. Ecol. 16, 604–607.

Caravaca, F., Barea, J.M., Figueroa, D., Roldán, A., 2002a. Assessing the effectiveness of mycorrhizal inoculation and soil compost addition for enhancing reafforestation with *Olea europaea* subsp. *sylvestris* through changes in soil biological and physical parameters. Appl. Soil Ecol. 20, 107–118.

Caravaca, F., Barea, J.M., Roldán, A., 2002b. Synergistic influence of an arbuscular mycorrhizal fungus and organic amendment on *Pistacia lentiscus* L. seedlings afforested in a degraded semiarid soil. Soil Biol. Biochem. 34, 1139–1145.

Caravaca, F., Figueroa, D., Azcon-Aguilar, C., Barea, J.M., Roldan, A., 2003a. Medium-term effects of mycorrhizal inoculation and composted municipal waste addition on the establishment of two Mediterranean shrub species under semi-arid field conditions. Agr. Ecosyst. Environ. 97, 95–105.

Caravaca, F., Figueroa, D., Roldán, A., Azcón-Aguilar, C., 2003b. Alteration in rhizosphere soil properties of afforested *Rhamnus lycioides* seedlings in short-term response to mycorrhizal inoculation with Glomus intraradices and organic amendment. Environ. Manage. 31, 412–420.

Cardinale, B.J., Wright, J.P., Cadotte, M.W., Carroll, I.T., Hector, A., Srivastava, D.S., Loreau, M., Weis, J.J., 2007. Impacts of plant diversity on biomass production increase through time because of species complementarity. Proc. Natl. Acad. Sci. U. S. A. 104, 18123–18128.

Celik, I., Ortas, I., Kilic, S., 2004. Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. Soil Till. Res. 78, 59–67.

Clements, F.E., 1916. Plant Succession: An Analysis of the Development of Vegetation. Carnegie Institution, Washington, DC.

Crecchio, C., Curci, M., Pizzigallo, M.D.R., Ricciuti, P., Ruggiero, P., 2004. Effects of municipal solid waste compost amendments on soil enzyme activities and bacterial genetic diversity. Soil Biol. Biochem. 36, 1595–1605.

Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Appl. Soil. Ecol. 15, 3–11.

Eriksen, G.N., Coale, F.J., Bollero, G.A., 1999. Soil nitrogen dynamics and maize production in municipal solid waste amended soil. Agron. J. 91, 1009–1016.

Frenot, Y., Gloaguen, J.C., Cannavacciuolo, M., Bellido, A., 1998. Primary succession on glacier forelands in the subantarctic Kerguelen Islands. J. Veg. Sci. 9, 75–84.

Gabrielle, B., Da-Silveira, J., Houot, S., Michelin, J., 2005. Field-scale modelling of carbon and nitrogen dynamics in soils amended with urban waste composts. Agr. Ecosyst. Environ. 110, 289–299.

García-Gil, J.C., Ceppi, S.B., Velasco, M.I., Polo, A., Senesi, N., 2004. Long-term effects of amendment with municipal solid waste compost on the elemental and acidic functional group composition and pH-buffer capacity of soil humic acids. Geoderma 121, 135–142.

Gaur, A., Adholeya, A., 2005. Diverse response of five ornamental plant species to mixed indigenous and single isolate arbuscular-mycorrhizal inocula in marginal soil amended with organic matter. J. Plant Nutr. 28, 707–723.

Glaser, B., 2007. Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. Philos. Trans. R. Soc. Lond., Ser. B: Biol. Sci. 362, 187–196.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. Biol. Fertil. Soils 35, 219–230.

Glenn-Lewin, D.C., van der Maarel, E., 1992. Patterns and processes of vegetation dynamics. In: Glenn-Lewis, D.C., Peet, R.K., Veblen, T.T. (Eds.), Plant Succession: Theory and Prediction. Chapmann and Hall, London, pp. 11–59.

Hannah, L., Carr, J.L., Lankerani, A., 1995. Human disturbance and natural habitat: a biome level analysis of a global data set. Biodivers. Conserv. 4, 128–155.

Hargreaves, J.C., Adl, M.S., Warman, P.R., 2008. A review of the use of composted municipal solid waste in agriculture. Agr. Ecosyst. Environ. 123, 1–14.

Harris, J., 2009. Soil microbial communities and restoration ecology: facilitators or followers? Science 325, 573–574.

Harte, J., Kinzig, A.P., 1993. Mutualism and competition between plants and decomposers: implications for nutrient allocation in ecosystems. Am. Nat. 141, 829–846.

van der Heijden, M.G.A., Klironomos, J.N., Ursic, M., Moutoglis, P., Streitwolf-Engel, R., Boller, T., Wiemken, A., Sanders, I.R., 1998. Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. Nature 396, 69–72.

van der Heijden, M.G., Bardgett, R.D., van Straalen, N.M., 2008. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol. Lett. 11, 296–310.

Heneghan, L., Miller, S.P., Baer, S., Callaham, M.A., Montgomery, J., Pavao-Zuckerman, M., Rhoades, C.C., Richardson, S., 2008. Integrating soil ecological knowledge into restoration management. Restor. Ecol. 16, 608–617.

Hodkinson, I.D., Webb, N.R., Coulson, S.J., 2002. Primary community assembly on land – the missing stages: why are the heterotrophic organisms always there first? J. Ecol. 90, 569–577.

Hooper, D.U., Chapin III, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecol. Monogr. 75, 3–35.

Iglesias-Jiménez, E., 2001. Nitrogen availability from a mature urban compost determined by the ^{15}N isotope dilution method. Soil Biol. Biochem. 33, 409–412.

Ishii, T., Kadoya, K., 1994. Effects of charcoal as a soil conditioner on citrus growth and vesicular–arbuscular mycorrhizal development. J. Jpn. Soc. Hortic. Sci. 63, 529–535.

Jackson, S.T., Hobbs, R.J., 2009. Ecological restoration in the light of ecological history. Science 325, 567–569.

Jakobsen, S.T., 1995. Aerobic decomposition of organic wastes 2. Value of compost as a fertilizer. Resour. Conserv. Recy. 13, 57–71.

Jansa, J., Mozafar, A., Anken, T., Ruh, R., Sanders, I., Frossard, E., 2002. Diversity and structure of AMF communities as affected by tillage in a temperate soil. Mycorrhiza 12, 225–234.

Jansa, J., Mozafar, A., Kuhn, G., Anken, T., Ruh, R., Sanders, I.R., Frossard, E., 2003. Soil tillage affects the community structure of mycorrhizal fungi in maize roots. Ecol. Appl. 13, 1164–1176.

Johnson, N.C., 1998. Responses of *Salsola kali* and *Panicum virgatum* to mycorrhizal fungi, phosphorus and soil organic matter: implications for reclamation. J. Appl. Ecol. 35, 86–94.

Kardol, P., Wardle, D.A., 2010. How understanding aboveground-belowground linkages can assist restoration ecology. Trends Ecol. Evol. 25, 670–679.

Kindscher, K., Wells, P.V., 1995. Prairie plant guilds: a multivariate analysis of prairie species based on ecological and morphological traits. Plant Ecol. 117, 29–50.

Klironomos, J.N., 2002. Feedback with soil biota contributes to plant rarity and invasiveness in communities. Nature 417, 67–70.

Klironomos, J.N., 2003. Variation in plant response to native and exotic arbuscular mycorrhizal fungi. Ecology 84, 2292–2301.

Knapp, A.K., Blair, J.M., Briggs, J.M., Collins, S.L., Hartnett, D.C., Johnson, L.C., Towne, E.G., 1999. The keystone role of bison in North American tallgrass prairie. BioScience 49, 39–50.

Knapp, A.K., Seastedt, T.R., 1986. Detritus accumulation limits productivity of tallgrass prairie. BioScience 36, 662–668.

Knapp, A.K., Smith, M.D., 2001. Variation among biomes in temporal dynamics of aboveground primary production. Science 291, 481–484.

Laird, D.A., 2008. The charcoal vision: a win win win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. Agron. J. 100, 178–181.

Lehmann, J., 2007. A handful of carbon. Nature 447, 143–144.

Lehmann, J., Joesph, S., 2009. Biochar for environmental management: an introduction. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management: Science and Technology. Earthscan, Dunstan House, London, UK.

Lehmann, J., Pereira da Silva, J., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249, 343–357.

Lehmann, J., Rondon, M., 2006. Bio-char soil management on highly weathered soils in the humid tropics. In: Uphoff, N. (Ed.), Biological Approaches to Sustainable Soil Systems. CRC Press, Boca Raton, FL, pp. 517–530.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J., 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Am. J. 70, 1719–1730.

Maherali, H., Klironomos, J.N., 2007. Influence of phylogeny on fungal community assembly and ecosystem functioning. Science 316, 1746–1748.

Major, J., Rondon, M., Molina, D., Riha, S., Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil 333, 117–128.

Matias, S.R., Pagano, M.C., Muzzi, F.C., Oliveira, C.A., Carneiro, A.A., Horta, S.N., Scotti, M.R., 2009. Effect of rhizobia, mycorrhizal fungi and phosphate-solubilizing microorganisms in the rhizosphere of native plants used to recover an iron ore area in Brazil. Eur. J. Soil Biol. 45, 259–266.

McCann, K.S., 2000. The diversity-stability debate. Nature 405, 228–233.

McConnell, D., Shiralipour, A., Smith, W., 1994. Compost impact on soil/plant properties. In: Composting Source Separated Organics. JG Press, Emmaus, PA, pp. 89–91.

McLauchlan, K., 2006. The nature and longevity of agricultural impacts on soil carbon and nutrients: a review. Ecosystems 9, 1364–1382.

Miller, R.M., Jastrow, J.D., 1992. The application of VA mycorrhizae to ecosystem restoration and reclamation. In: Allen, M.F. (Ed.), Mycorrhizal Functioning: An Integrative Plant-Fungal Process. Chapman and Hall, New York, NY, pp. 438–467.

Mkhabela, M.S., Warman, P.R., 2005. The influence of municipal solid waste compost on yield, soil phosphorus availability and uptake by two vegetable crops grown in a Pugwash sandy loam soil in Nova Scotia. Agr. Ecosyst. Environ. 106, 57–67.

Montemurro, F., Maiorana, M., Convertini, G., Ferri, D., 2006. Compost organic amendments in fodder crops: effects on yield, nitrogen utilization and soil characteristics. Compost. Sci. Util. 14, 114–123.

del Moral, R., Walker, L., Bakker, J., 2007. Insights gained from succession for the restoration of landscape structure and function. In: Walker, L.R., Walker, J., Hobbs, R.J. (Eds.), Linking Restoration and Ecological Succession. Springer, New York, NY, pp. 19–44.

Movahedi-Naeini, S.A.R., Cook, H.F., 2000. Influence of municipal compost on temperature, water, nutrient status and the yield of maize in a temperate soil. Soil Use Manage. 16, 215–221.

Mummey, D.L., Antunes, P.M., Rillig, M.C., 2009. Arbuscular mycorrhizal fungi pre-inoculant identity determines community composition in roots. Soil Biol. Biochem. 41, 1173–1179.

Nemergut, D.R., Anderson, S.P., Cleveland, C.C., Martin, A.P., Miller, A.E., Seimon, A., Schmidt, S.K., 2007. Microbial community succession in an unvegetated, recently deglaciated soil. Microb. Ecol. 53, 110–122.

Nguyen, B.T., Lehmann, J., Kinyangi, J., Smernik, R., Riha, S.J., Engelhard, M.H., 2008. Long-term black carbon dynamics in cultivated soil. Biogeochemistry 89, 295–308.

Nishio, M., Okano, S., 1991. Stimulation of the growth of alfalfa and infection of roots with indigenous vesicular–arbuscular mycorrhizal fungi by the application of charcoal. Bull. Natl. Grassi. Res. Inst. 45, 61–71.

Novak, J.M., Busscher, W.J., Laird, D.L., Ahmedna, M., Watts, D.W., Niandou, M.A.S., 2009. Impact of biochar amendment on fertility of a southeastern coastal plain soil. Soil Sci. 174, 105–112.

Noyd, R.K., Pfleger, F.L., Norland, M.R., 1996. Field responses to added organic matter, arbuscular mycorrhizal fungi, and fertilizer in reclamation of taconite iron ore tailing. Plant Soil 179, 89–97.

Odum, E.P., 1969. The strategy of ecosystem development. Science 164, 262–270.

Oelmann, Y., Wilcke, W., Temperton, V.M., Buchmann, N., Roscher, C., Schumacher, J., Schulze, E.D., Weisser, W.W., 2007. Soil and plant nitrogen pools as related to plant diversity in an experimental grassland. Soil Sci. Am. J. 71, 720–729.

Ojima, D.S., Dirks, B.O., Glenn, E.P., Owensby, C.E., Scurlock, J.O., 1993. Assessment of C budget for grasslands and drylands of the world. Water Air Soil Pollut. 70, 95–109.

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, J.C., Seastedt, T., Moya, E.G., 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Glob. Biogeochem. Cy. 7, 785–809.

Pascual, J.A., García, C., Hernandez, T., 1999. Lasting microbiological and biochemical effects of the addition of municipal solid waste to an arid soil. Biol. Fertil. Soils 30, 1–6.

Pimm, S.L., 1991. The Balance of Nature? Ecological Issues in the Conservation of Species and Communities. University of Chicago Press, Chicago, IL.

Piper, J.K., Pimm, S.L., 2002. The creation of diverse prairie-like communities. Comm. Ecol. 3, 205–216.

Pokorny, M.L., Sheley, R.L., Svejcar, T.J., Engel, R.E., 2004. Plant species diversity in a grassland plant community: evidence for forbs as a critical management consideration. West. N. Am. Nat. 64, 219–230.

Pywell, R.F., Bullock, J.M., Hopkins, A., Walker, K.J., Sparks, T.H., Burke, M.J.W., Peel, S., 2002. Restoration of species rich grassland on arable land: assessing the limiting processes using a multi-site experiment. J. Appl. Ecol. 39, 294–309.

Reynolds, H.L., Packer, A., Bever, J.D., Clay, K., 2003. Grassroots ecology: plant–microbe–soil interactions as drivers of plant community structure and dynamics. Ecology 84, 2281–2291.

Rillig, M.C., 2004. Arbuscular mycorrhizae and terrestrial ecosystem processes. Ecol. Lett. 7, 740–754.

Risser, P.G., Parton, W.J., 1982. Ecosystem analysis of the tallgrass prairie: nitrogen cycle. Ecology 63, 1342–1351.

Rondon, M., Lehmann, J., Ramirez, J., Hurtado, M., 2007. Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. Biol. Fertil. Soils 43, 699–708.

Rondon, M., Ramirez, A., Hurtado, M., 2004. Charcoal Additions to High Fertility Ditches Enhance Yields and Quality of Cash Crops in Andean Hillsides of Columbia (CIAT Annual Report 2004). Cali, Colombia.

Ros, M., Hernandez, M.T., Garcia, C., 2003. Soil microbial activity after restoration of a semiarid soil by organic amendments. Soil Biol. Biochem. 35, 463–469.

Ros, M., Klammer, S., Knapp, B., Aichberger, K., Insam, H., 2006. Long-term effects of compost amendment of soil on functional and structural diversity and microbial activity. Soil Use Manage. 22, 209–218.

Ruiz-Jaen, M.C., Aide, M., 2005. Restoration success: how is it being measured? Restor. Ecol. 13, 569–577.

Sala, O.E., Parton, W.J., Joyce, L.A., Lauenroth, W.K., 1988. Primary production of the central grassland region of the United States. Ecology 69, 40–45.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.

Schmidt, M.W.I., Noack, A.G., 2000. Black carbon in soils and sediments. Analysis, distribution, implications, and current challenges. Glob. Biogeochem. Cy. 14, 777–793.

Schwartz, M.W., Hoeksema, J.D., Gehring, C.A., Johnson, N.C., Klironomos, J.N., Abbott, L.K., Pringle, A., 2006. The promise and the potential consequences of the global transport of mycorrhizal fungal inoculum. Ecol. Lett. 9, 501–515.

Shrestha, G., Traina, S.J., Swanston, C.W., 2010. Black carbon's properties and role in the environment: a comprehensive review. Sustainability 2, 294–320.

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Till. Res. 79, 7–31.

Skjemstad, J.O., Reicosky, D.C., Wilts, A.R., McGowan, J.A., 2002. Charcoal carbon in US agricultural soils. Soil Sci. Am. J. 66, 1249–1255.

Smith, J.L., Collins, H., Bailey, V.L., 2010. The effect of young biochar on soil respiration. Soil Biol. Biochem. 42, 2345–2347.

Smith, S.E., Read, D.J., 2008. Mycorrhizal Symbiosis, 3rd ed. Academic Press, New York, NY.

Smith, V.C., Bradford, M.A., 2003. Litter quality impacts on grassland litter decomposition are differently dependent on soil fauna across time. Appl. Soil Ecol. 24, 197–203.

Sohi, S., Lopez-Capel, E., Krull, E., Bol, R., 2009. Biochar, climate change and soil: a review to guide future research (CSIRO Land and Water Science Report 05/09).

Suding, K.N., Gross, K.L., Houseman, G.R., 2004. Alternative states and positive feedbacks in restoration ecology. Trends Ecol. Evol. 19, 46–53.

Thies, J.E., Rillig, M.C., 2009. Characteristics of biochar: biological properties. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management: Science and Technology. Earthscan, Dunstan House, London, UK.

Tieszen, L.L., Reed, B.C., Bliss, N.B., Wylie, B.K., DeJong, D.D., 1997. NDVI, C3 and C4 production, and distributions in Great Plains grassland land cover classes. Ecol. Appl. 7, 59–78.

Tilman, D., Downing, J.A., 1994. Biodiversity and stability in grasslands. Nature 367, 363–365.

Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., Siemann, E., 1997. The influence of functional diversity and composition on ecosystem processes. Science 277, 1300–1302.

Tscherko, D., Rustemeier, J., Richter, A., Wanek, W., Kandeler, E., 2003. Functional diversity of the soil microflora in primary succession across two glacier forelands in the Central Alps. Eur. J. Soil Sci. 54, 685–696.

Wahba, M.M., Darwish, K.M., 2008. Micro-morphological changes of sandy soils through the application of compost manure. J. Appl. Biol. Sci. 2, 95–98.

Walker, L.R., Walker, J., del Moral, R., 2007. Forging a new alliance between succession and restoration. In: Walker, L.R., Walker, J., Hobbs, R.J. (Eds.), Linking Restoration and Ecological Succession. Springer, New York, NY, pp. 1–18.

Walter, I., Martinez, F., Cuevas, G., 2006. Plant and soil responses to the application of composted MSW in a degraded, semiarid shrubland in central Spain. Compost. Sci. Util. 14, 147–154.

Wardle, D.A., Bardgett, R.D., Klironomos, J.N., Setälä, H., van der Putten, W.H., Wall, D.H., 2004. Ecological linkages between aboveground and belowground biota. Science 304, 1629–1633.

Wardle, D.A., Bonner, K.I., Barker, G.M., 2002. Linkages between plant litter decomposition, litter quality, and vegetation responses to herbivores. Funct. Ecol. 16, 585–595.

Wardle, D.A., Zackrisson, O., Nilsson, M.C., 1998. The charcoal effect in Boreal forests: mechanisms and ecological consequences. Oecologia 115, 419–426.

Warnock, D.D., Lehmann, J., Kuyper, T.W., Rillig, M.C., 2007. Mycorrhizal responses to biochar in soil – concepts and mechanisms. Plant Soil 300, 9–20.

Weber, J., Karczewska, A., Drozd, J., Licznar, M., Licznar, S., Jamroz, E., Kocowicz, A., 2007. Agricultural and ecological aspects of a sandy soil as affected by the application of municipal solid waste composts. Soil Biol. Biochem. 39, 1294–1302.

Wolkowski, R.P., 2003. Nitrogen management considerations for landspreading municipal solid waste compost. J. Environ. Qual. 32, 1844–1850.

Wortmann, C.S., Walters, D.T., 2007. Residual effects of compost and plowing on phosphorus and sediment in runoff. J. Environ. Qual. 36, 1521–1527.