Application of Wood Ash, Biosolids, and Papermill Residuals to Forest Soils
– A Review of the Literature

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STAFF PAPER SERIES NUMBER 153

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Research supported by the University of Minnesota's College of Natural Resources, the Minnesota Agricultural Experiment Station, and the Minnesota Legislature ML 1999, Chap. 231, Sec. 16, Subd. 10(g) as recommended by the Legislative Commission on Minnesota Resources.

Contents

Abstract

Industrial and municipal by-products have been used as agricultural soil amendments for decades, and more recently, as forest soil amendments. We reviewed the effects of by-products: wood ash, biosolids (sewage sludge), and papermill residuals (papermill sludge) on tree growth and forest ecosystems. We examined the effects of soils amended with by-products on foliar metal (e.g., Ni, Cr, Cd) and nutrient concentrations, soil chemical and physical properties, metal and nutrient leaching, runoff, and general effects on microbes, insects, flora and fauna. It is difficult to determine maximum by-product application rates from the literature and generalize this information to other regions due to the physical and chemical variation in soils and by-products studied. Nonetheless, information on maximum by-product application rates is useful. We present values from the literature that show increased tree growth without detrimental effects on forest ecosystem function with the caveat that results from these studies be validated regionally before their usage. Maximum application rates derived from the literature for: wood ash were 6 Mg ha^{-1} $CaCO_3$ (frequency of application not specified) on low pH forest soils; biosolids were a rate equivalent to 250 kg ha^{-1} yr^{-1} total nitrogen (N); and papermill residuals were a rate equivalent to 300 kg ha^{-1} total N (frequency not specified). There has been little research on the coapplication effects of two or more of these amendments on forest land. We recommend possible coapplication strategies for future research based on the properties of the amendments and their effects. Wood ash increases soil pH and has been found beneficial to tree growth on acidic soils, but is low in N, therefore coapplication with N-rich biosolids is recommended if a site is also N-deficient. Both biosolids and papermill residuals have beneficial effects on tree growth, but the high C:N ratio of papermill residuals results in short term immobilization of N. The coapplication of papermill residuals with biosolids may ameliorate this short term N immobilization. Nitrate leaching after biosolids application may be prevented by using proper site specific maximum application rates, and/or coapplication with N immobilizing by-products (e.g., papermill residuals). By-product application to forest soils is a potentially viable, environmentally sound method of disposing industrial and municipal waste products while enhancing tree growth.

Introduction

This paper reviews the recent literature pertaining to the land application of wood ash, biosolids, and papermill residuals, and their impact on forest soils. These by-products vary in their chemical and physical characteristics. Wood ash is generated from incineration of wood waste. In some cases wood and/or bark chips are burned with other material such as coal, papermill residuals or other similar by-products. In Minnesota, wood ash may contain up to 49% coal ash and still be considered wood ash from a regulatory perspective. Chemical composition of ash by-products is affected by the material incinerated and plant operational procedures, but in general it contains macronutrients and micronutrients such as potassium (K) and boron (B).

Biosolids are the by-products of residential and/or industrial wastewater treatment. For example, water treatment facilities located in Grand Rapids, Minnesota, combine residential wastewater with paper and pulpmill residue from a papermill facility. Wastewater treatment plants may use primary or secondary treatments or a combination of both. Municipalities having only primary processing facilities are usually restricted from land application of their biosolids due to potential concern for waste born pathogens. Biosolids contain nitrogen (N) and phosphorus (P) and may be land applied either in dry form or as liquid slurry.

Papermill residuals can be applied as primary or secondary residuals or a combination of both. Primary residuals are derived from organic and inorganic materials in untreated mill wastewater. They can be mechanically dewatered and usually contain 20-45% solids. The organic component is primarily wood fiber, nitrogen and phosphorus. The inorganic component consists of clay, calcium carbonate, titanium dioxide, and other materials. Secondary papermill residuals are created from the sedimentation of biologically treated waste water and composed mostly of microbial biomass with high concentrations of N and P. Secondary material does not dewater well and therefore is usually combined with primary residuals and may constitute 5% to 75% of the combined papermill residual.

The purpose of by-product application to forest soils is to: (1) beneficially recycle nutrients back to the soil, (2) decrease disposal costs, and (3) improve tree growth. Plant yield is the most important parameter measured for quantifying the effect of by-product application. Another parameter measured is the elemental composition of tree leaves. Nutrient and heavy metal status can be determined through analysis of foliar tissue and its comparison with established norms (if such information is available). Other issues we address in this review are heavy metal and nutrient leaching, nutrient runoff, and application rates that minimize detrimental effects on biological soil function, nutrient status and other forest organisms. We cannot stress enough the importance of a full analysis of the amendment material before application. A program can then be developed to determine threshold levels of by-product application to ensure environmentally sound by-product utilization practices.

By-product Effects on Plant Yield

Wood Ash

In general, tree growth has been shown to increase with the addition of wood ash, especially on acidic forest soils. A study of a Scots pine (*Pinus sylvestris*) stand in the organic soils of Finland showed a 30-fold increase in wood fiber yield 41 years after ash application rates up to 16 Mg ha^{-1} (Silfverberg and Hotanen 1989). Also in Finland, there was a 65% increase in productivity of willow root cuttings one year after the application of ash at the rate of 10 Mg ha^{-1} (Weber et al. 1985). In another study, symptoms of nutrient disorders and dieback were reduced and fiber yields increased 5-fold in a Scots pine stand 13 years after the application of 20 Mg ha^{-1} of wood bark ash (Ferm et al. 1992).

Although most of the positive effects associated with wood ash application have been reported in European studies, the potential for ash utilization in North America is great. Increases in tree growth in response to ash application have mainly been attributed to increases in availability of soil K, P, and B (Vance 1996). The liming effect of the ash creates a more favorable pH for tree growth in low pH forest soils (Pritchett and Fisher 1987). A greenhouse study with poplar (*Populus* sp.) grown in three different silt loam soils from Idaho showed an increase in growth rate (15% diameter and 9% height) two months after wood ash amendment at 2% of soil volume (Etiegni et al. 1991). A 3:1 fish silage: wood ash mixture supplying 504 kg ha^{-1} total N and 5 Mg ha^{-1} of ash enhanced the height and diameter growth of a 9-year-old western red cedar (*Thuja plicata*) plantation in coastal British Columbia (McDonald et al 1994).

Biosolids

On a dry weight basis, biosolids typically contain 1 to 10% total nitrogen (Crohn 1995) and 1 to 4% phosphorus (Sommers 1977). Biosolids have been used as an agricultural soil amendment in the United States and Europe, and utilization of biosolids as soil amendments for forest land has been studied in the United States since the 1960s (Dutch and Wolstenholme 1994). A long-term study in progress for the past 20 years under the Pack Forest Sludge Research Program at the University of Washington (Henry et al. 1994) has focused on Douglas-fir (*Pseudotsuga menziesii*). In a six-year study of a 60-year-old stand, there was a 48% and 93% increase in average six year diameter growth of the unthinned and thinned biosolid treated stands respectively as compared to the untreated plots (Cole et al. 1984). Young Douglas-fir stands responded better to soil amendments than established stands, which has led to recommendations of biosolids application to clearcuts before replanting (Henry et al. 1994).

Simulation studies using data from the Hubbard Brook Experimental Forest in New Hampshire, where N is known to be limiting, suggest positive impacts from biosolids application. Simulated additions of 4 Mg ha^{-1} of anaerobically digested biosolids (dry mass, 0.05 solid N fraction, 0.7 to 0.8 organic N, 0.2 to 0.3 labile N) every three years to a 30-year-old hardwood stand is predicted to increase harvestable biomass by 24.6% over a 50-year period (Crohn 1995). Another computer simulation compared the effects of biosolids application on fiber yields in different parts of the United States. This simulation suggested the highest relative growth response for Douglas-fir in the Pacific Northwest, a moderate growth increase for southern loblolly pine (*Pinus taeda*) in the southeast with relatively lower increases in yield in northern hardwood forests in the northeast (Luxmoore et al. 1999).

Over application of biosolids can result in a reduction of tree growth. In Washington, the addition of high rates of municipal biosolids to Douglas-fir and Grand fir (*Abies grandis*) plantations resulted in foliar chlorosis and reduced growth rates (Harrison et al. 1996). The excess N increased rates of nitrification and consequently acidification, which in turn increased cation leaching, thus depleting supplies of exchangeable Mg (Harrison et al. 1996). In this case, the coapplication of wood ash with biosolids may have ameliorated the negative impacts of soil acidification.

Papermill Residuals

There is evidence of tree growth enhancement through the addition of papermill (or pulpmill) residue, suggesting its potential as a soil amendment. A 14-month study in a 40-year-old red pine (*Pinus resinosa*) plantation in northwestern Michigan showed a 35% increase in foliar dry mass, a 22% increase in needle length, and a 12% increase in diameter growth from papermill residuals at application rates ranging from 16 to 32 Mg ha^{-1} (1130 to 2260 kg ha^{-1} total N) (Brockway 1983). There have also been land reclamation projects that utilize pulp or papermill residuals as an amendment to improve tree establishment and growth on disturbed or degraded sites. Coal mine spoils in Ohio were amended with papermill residuals at high rates of application of 860 Mg ha^{-1} per 15 cm of soil depth (5.8 Mg ha^{-1} total N) and the survival and growth rate of white ash (*Fraxinus americana*), sycamore (*Plantanus occidentalis*), and black walnut (*Juglans nigra*) were enhanced (Kost et al. 1997).

Land application of primary pulpmill residuals with a high carbon to nitrogen (C:N) ratio induces N immobilization (Cabral et al. 1998). There are two ways to adjust this ratio to avoid depressed N uptake. One way is to add the biosolids before planting (Cabral et al. 1998) and allow sufficient time for N mineralization to occur. If immediate planting is desired or the stand is already established, however, additional N inputs (biosolids or fertilizer) would help the microorganisms to break down the pulp residual without reducing N availability (Cabral et al. 1998).

By-product Effects on Foliar Nutrient Concentrations

Wood Ash

In a study in Finland, Lumme and Laiho (1988) found that wood ash application increased the concentrations of both P and K in willow (*Salix aquatica*) foliage and bark, but did not affect N. In the same study, one application of ash at the rate of 5 Mg ha^{-1} increased Ca and Mg concentrations in leaf and bark tissue. Calcium and Mg tissue concentrations decreased at the ash application rates of 20 M ha^{-1}, suggesting a nutrient imbalance at higher wood ash application rates for this soil and species combination. Application of wood ash at rates of 10-20 Mg ha^{-1} alleviated K and B deficiencies for a 13-year period in Scots pine and downy birch (*Betula pubescens*) in Finland (Ferm et al. 1992). Neither N nor P concentrations were affected, presumably because there was no deficiency in these nutrients (Ferm et al. 1992). Application of wood ash to a 9-year-old western red cedar at a rate of 5 Mg ha^{-1} did not affect foliar N, P, K, Ca, or Mg concentrations following two growing seasons on soils having low N concentrations in western Canada (McDonald et al. 1994).

Biosolids

Excessive rates of biosolid application to a forest site may cause trace metal phytotoxicity or soil acidification. Forest soils usually have a low pH and a further reduction in soil pH can result in macronutrient deficiencies through cation leaching. Nutrient imbalances may also result. For example, in Washington, a severe foliar Mg deficiency was found in Douglas-fir and Grand fir 10 years after application of a biosolid amendment having a total N equivalent of 8 Mg ha^{-1} (Harrison and Henry 1994). Foliar levels of Ni, Cd, and Cr were found significantly elevated, but not toxic (Harrison and Henry 1994). No changes were detected in other foliar trace metals (Zn, Cu, Cr, Pb, Ni), or foliar P concentrations, but increases in foliar N were detected following application of biosolids having a total N equivalent of 1,160 kg ha^{-1} in red pine (*Pinus resinosa*) and white pine (*Pinus strobus*) plantations in Michigan (Brockway 1983). Preplanting application of biosolids at rates of 13 and 26 Mg dry solids ha^{-1} having total N equivalents of 445 and 893 kg ha^{-1} and total P equivalents of 128 and 256 kg ha^{-1} on a Sitka spruce (*Picea sitchensis*) plantation resulted in a significant increase in foliar and soil Cu and Zn concentrations seven years after planting (Dutch and Wolstenholme 1994). Foliar N levels declined during the five years after application from sufficient to deficient, while foliar P remained sufficient throughout the study (Dutch and Wolstenholme 1994). Application of biosolids slurry at rates of 3.3 and 4.8 dry Mg ha^{-1} supplying N equivalents of 190 and 290 kg ha^{-1}, respectively, on a 43-year-old Scots pine plantation in Scotland resulted in increases in foliar N but no change in foliar P or K after one year (Ferrier et al. 1996). In a two-year study of clonal willow (*Salix aquatica*) in Finland, foliar N and P increased but foliar K decreased in comparison to control treatments at biosolids application rates of 14.4 dry Mg ha^{-1} at 3.5% total N (Lumme and Laiho 1988). Both Lumme and Laiho (1988) and Dutch and Wolstenholme (1994) reported foliar N increases due to biosolids to be similar to those from comparable N application rates from inorganic fertilizers. McDonald et al. (1994) applied 69 Mg ha^{-1} of biosolids slurry (26% solid) having a total N content of 542 kg ha^{-1} and P content of 162 kg ha^{-1} to a 9-year-old western red cedar plantation and reported increases in foliar N, P, Ca, and Mg after year one that decreased in year two. Collectively, these studies suggest biosolid applications affect tree nutrition immediately and this impact diminishes over time.

Papermill Residuals

The effects of papermill residuals application on forest foliar nutrients concentrations are not well documented. Characterizing this type of by-product before application is especially important because of the wide range of processing methods and their impact on nutrients and metal concentrations. Approximately 40% of all papermill residuals are derived from primary waste treatment processing and contain wood fibers with C:N ratios ranging from 100:1 to 300:1 (Vance 2000). Secondary papermill residuals have more nutrients with a C:N ratio range of 5:1 to 20:1 (Cabral et al. 1998).

Vasconcelos and Cabral (1993) suggested that papermill residuals applications of less than 80 Mg ha^{-1} yr^{-1} would create no serious problems with metal toxicity. In Michigan, foliar N concentrations for red and white pine increased while the foliar P concentrations were not affected by papermill residuals amendment at the rate of 4, 8, 16, and 32 Mg ha^{-1} having total P concentrations of 40, 80, 160, and 620 kg ha^{-1}, respectively (Brockway 1983). Kost et al. (1997) used two application rates of papermill residuals: 860 Mg ha^{-1} incorporated into the upper 15 cm; and 3450 Mg ha^{-1} incorporated into the upper 60 cm with total N equivalents of 5.8 Mg ha^{-1} and 23.1 Mg ha^{-1} in low pH mine tailings. They detected adequate foliar N concentrations in white ash, sycamore, and black walnut four years following biosolids application for each application rate.

By-product Effects on Soil Properties

Wood Ash

A summary of the effect of wood ash on the chemical properties and forest soil ecosystems in Europe and in North America is presented in Table 1. Additions of wood ash even at rates as low as 1 Mg ha^{-1} have been shown to increase soil pH (Ferm et al. 1992) and enhance plant uptake of most macronutrients in low pH forest soils (Pritchett and Fisher 1987).

Biosolids

An inconsistency in reporting methodology for biosolid studies has caused substantial confusion in the literature. Application rates are not given uniformly and the N content of the material is often not specified (total or available) and/or reported. The effects of biosolids amendments on forest soil pH are variable but biosolids application usually increases soil N (Table 2).

Papermill Residuals

The impact of amending forest soils with papermill residuals has not been well studied. Papermill residuals have a high organic matter content and in addition to improving soil chemical properties it increases soil moisture holding capacity, improves soil aeration, reduces soil bulk density, and increases soil stability (Cabral et al. 1998). Papermill residuals application of 40 Mg ha^{-1} increased soil pH, exchangeable Ca and Mg, cation exchange capacity, and percent base saturation in Maine (Kraske and Fernandez 1993). Soil properties most affected in the long term by pulpmill residuals appear to be exchangeable Na, Mg, and SO_4^{-2} (Kraske and Fernandez 1993). In the US Great Lake states, Brockway (1983) reported an increase in forest floor N, P, total salt, and soil pH at application rates of 4, 8, 16, and 32 Mg ha^{-1} having total N equivalents of 282, 565, 1130, and 2260 kg ha^{-1}, respectively.

Impacts of By-product Applications on Leaching and Runoff

Wood Ash

In a thorough review of the current literature, Someshwar (1999) suggested that the levels of traditional organics of environmental concern found in wood ash generated from the combustion of papermill residuals were negligible. In a separate literature review, Vance (1996) suggested that an ash application rate of 10 Mg ha^{-1} would result in metal (Cd, Cr, Co, Cu, Pb) loadings close to two orders of magnitude less than the limits set by the US Environmental Protection Agency (EPA) for biosolids. In another study, application rates up to 44 Mg ha^{-1} on forest soil in the southern United States did not increase the concentration of Ca, K, Cd, Cr, Cu, Ni, and As in the ground water above the standards for drinking water established by the EPA (Williams et al. 1996).

Characterization of ash before its application is important, however. A column study of papermill ashes found significant amounts of Cr, Se, Zn, and Cu leaching, therefore, acidification to increase the solubility of metals followed by preleaching of the ash was recommended before application (Xiao et al. 1999). Some ashes that are derived from papermill residuals contain organic compounds of potential human health concerns such as polychlorinated dibenzo-p-dioxins (PCCDs) and polychlorinated dibenzofurans (PCDFs) while other ashes are salt-laden because they were derived from wood stored or transported on ocean water (Vance 1996).

Biosolids

The EPA drinking water standard is 10 mg of nitrate N L^{-1} of water. One of the goals of biosolid application research has been to determine the application rate that will maximize plant yield with minimum nitrate leaching (or at least below the EPA standard). Results in literature are variable, due to factors such as soil type, vegetation, climate, etc. In general, the highest application rates that do not result in excessive nitrate leaching are in the range of 250 kg ha^{-1} total N equivalent (see Table 3). There are also public health concerns of soil contamination with trace metals and pathogens from repeated application of untreated biosolids in forests. Pathogens tend to persist less than a year, but trace metals associated with biosolids tend to persist in the environment for a much longer period (Henry et al. 1994).

Phosphorus (P) runoff is also a concern with the application of biosolids. The amount of P generally added in biosolids application to forest soils is small compared to the soil pool of total P, but the requirements for tree and understory uptake are usually exceeded in just one application, assuming a biosolids P content of 0.5% (Grey and Henry 1993). There are many variables, however, in the mobility of P after biosolid application and the percentage of P in biosolids (from 0.1% to14% on a dry solid basis, McLaughlin 1983). Forests vary greatly in their infiltration capacity because of different soil and cover types. The method of biosolids processing may also affect P mobility.

Anaerobically digested biosolids contain a higher percentage of inorganic P than aerobically digested biosolids (Grey and Henry 1993). There have only been a few studies involving P runoff after biosolid application to forest soils. At Pack Forest in Washington, no significant difference in P was found in runoff waters between treated and untreated sites one year after an application of 45 Mg ha^{-1} liquid biosolid slurry (University of Washington 1986). Significant P runoff was reported in Queensland, Australia after a 90 Mg ha^{-1}dry weight biosolids application to a *Pinus radiata* plantation (Loch et al. 1995), but these results are somewhat misleading because the authors did not use buffer zones between plots and collection sites. In operational application sites, buffer zones are essential. In agricultural application of biosolids, it was found that most soils are able to retain large amounts of P in an insoluble form and plants can withstand high soil P concentrations (McLaughlin 1983). In general, temperate forests have very high infiltration rates due to porous forest floor and soil properties. Because of this, overland flow runoff is minimal and therefore P runoff is likely to be minimal, but more research is needed with regard to maximum slope and buffer width.

Papermill Residuals

As with biosolids application, the goal of experiments with papermill residuals has been to find the application level that will maximize plant yield and minimize nitrate leaching. Experimental trials with papermill residuals have had higher N application rates than those for biosolids (Tables 3 and 4). Limited data show that EPA drinking water standards are not exceeded with papermill residuals application rates having total N equivalents of less than 300 kg ha^{-1} (Table 4). N equivalent application rates for papermill residuals can likely be higher because N is immobilized as a result of the high C:N ratio of papermill residuals.

Effects of By-product Applications on Forest Ecosystems

Wood Ash

A study in Sweden reported a decrease in the total microbial biomass at an ash application rate of 5.0 Mg ha^{-1}, but no change was detected at lower application rates (Baath et al. 1994). Other studies (Table 1) have reported an increase in microbial activity following ash amendments in low pH forest soils (e.g., Weber et al. 1985; Fritze et al. 1994).

Densities of grass increased and mosses decreased following the addition of ash on Histosols in Finland (Ferm et al. 1992), which has important implications in the successional trajectory of the forest. In Sweden, acidic deposition has been correlated with increased spread of braken fern (*Pteridium aquilinum*), a fern with a circumpolar range that is allelopathic to certain tree seedlings (Gilmore 1999) and a strong competitor to conifer seedlings (Dolling 1996). Dolling (1996) hypothesized that since *P. aquilinum* flourishes in acidic soils, the addition of wood ash would raise the pH and therefore inhibit the growth of this fern. The amount of *P. aquilinum* was not affected at wood ash application rates of 2.2 M kg ha^{-1} (Dolling 1996).

Biosolids

Increased concentrations of Zn, Cu, Ni, and Cd were found to decrease microbial activity in sandy loam soils in the United Kingdom when biosolids were applied as a forest soil amendment having concentrations of heavy metals above the European Union limit for (300µg Cu, 75 µg Ni, 3 µg Cd and 140 µg Zn g^{-1} soil). Microbial biomass was not affected at biosolids application rates within the EU limit (Chander et al. 1995).

Fertilization of a young coniferous forest with biosolids having an N equivalent rate of 416 kg ha^{-1} in British Columbia did not affect the population size, body weight, or species diversity of small mammals one year after application (Cheng et al. 1996). Trace metal accumulation in animal tissue as a result of biosolids application has not been found to significantly increase throughout the food chain (Henry et al. 1994). However, statistically significant but biologically insignificant Cd concentration increases have been detected in mice and shrews in biosolids amended sites at the Pack Demonstration Forest in Washington (Nickelson and West 1996).

Papermill Residuals

Due to the high C:N ratio of this type of by-product, soil N is initially depleted in forest soils immediately following application. A decrease in growth rate of desired tree species can occur due to the increased competitive edge of undesired plant species more adapted to N-deficient conditions (Harrison et al. 1996). For example, understory growth in a red and white pine plantation in Michigan decreased significantly in the first two months after papermill residuals application, but then increased dramatically compared to control plots two years after application (Brockway 1983).

A major environmental concern in the application of papermill residuals is an increase in the concentrations of organo-chlorine compounds in the soil and groundwater due to addition of this material during the bleaching process (Cabral et al. 1998). The hazards may be minimized with pretreatment, composting or even a change in the plant bleaching processes (Cabral et al. 1998). There has been some effort to determine threshold levels of toxicity. For example Keenan et al. (1990) suggested that a soil concentration of 50 ppt of 2, 3, 7, 8 tetrachlorodibenzeno-p-dioxin (TCDD) would be the limit of toxicity for the American woodcock, a sensitive indicator species.

Summary

There is tremendous variation in forest soils within and between given locations. This makes broad guidelines for the application of wood ash, biosolids, and papermill residuals difficult. One feature that is common to the majority of forest soils in Midwestern and northeastern North America and Europe is their low pH. There are suggestions in the literature for maximum safe application rates of these three amendments covered in this review that would suffice as working hypotheses for future by-products research. Chemical characterization of by-products and forest soils before application is essential in the development of site-specific application and coapplication recommendation rates.

Maximum application rates of wood ash, biosolids, and papermill residuals are suggested through a few select studies. Kahl et al. (1996) found that wood ash applied at a $CaCO_3$ equivalent of 6 Mg ha^{-1} on acidic (average pH 4.5) soils of Maine increased soil cation exchange capacity without detrimentally affecting solution chemistry. Above this rate soil exchange sites were unable to buffer ash amendments and altered soil solution chemistry. Lower application rates, however, have been shown to increase soil pH (Ferm et al. 1992). Higher pH forest soils tended to have a greater leaching of nitrates following the application of by-products high in N (Tables 2 and 3). A conservative annual application rate for biosolids having a total N equivalent of 250 kg ha^{-1} yr^{-1} (220 lb ac^{-1} yr^{-1}) has been recommended for acidic forest soils in Europe (Riddel-Black 1998). Limited data show that EPA drinking water standards are not exceeded with papermill residuals application rates having total N equivalents of less than 300 kg ha^{-1} (Table 3). Maximum rates of papermill residuals tend to be higher than maximum rates of biosolids because the high C:N ratio of papermill residuals results in N immobilization, and for the short term, reduces the risk of excessive nitrate leaching.

The possibilities for environmentally sound coapplication strategies are optimistic, but more research is required to find optimal coapplication rates and ratios that minimize potential negative results. Wood ash is an important soil amendment that often increases pH and the availability of K, P, Mg, Ca, and Mg, depending on the ash composition. Due to the lack of N in wood ash, combining wood ash with complimentary amendments having high N concentrations would be advisable. Biosolid/ash coapplications are recommended because biosolids provide a more immediate supply of N and P. The N immobilizing effect of papermill residuals may be ameliorated by coapplication with biosolids. Coapplication of biosolids and papermill residuals may also be advisable if nitrate leaching is a concern. Mixing primary papermill residuals with biosolids would immobilize N and reduce biosolid nitrate leaching. By-products can serve as effective fertilizer substitutes, aid in the reversal of the effects of acidic deposition, aid in the reclamation of mine spoils, and replace soil nutrients removed from forests through timber harvesting.

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Table 1. Summary of reported studies on the effects of wood ash application on chemical properties and ecology of forest soils.

Species/ Location	Application Rate, Mg ha^{-1}	Study Duration	Soil pH Change	Chemical Change[a]	Ecological Impacts[a]	Source
Willow/Finland	10	3 years	4.6 to 5.5	(+) N mineralization (+) N fixation	(+) microbial activity	Weber et al. 1985
Willow/ Finland	5 20	2 years	6.5 to 7.0 7.5 to 8.2	(nc) nitrates (+) soluble P (+) exchangeable K,Mg,Ca	(nc) microbial activity	Lumme and Laiho 1988
Norway spruce/ Sweden	4	18 months	4.5 to 4.8	(nc) soluble P	---	Clarholm 1994
Loblolly pine/ North Carolina	11 22 44	15 months	4.0 to 4.5 4.0 to 5.0 4.0 to 6.6	(+) exchangeable K, Mg (nc) soluble P	---	Williams et al. 1996
Scots pine, downy birch/ Finland	2 5 10 20	12 years	5.2 to 5.3 5.2 to 5.4 5.2 to 5.5 5.2 to 5.6	(+) N mineralization (+) exchangeable K, B	(+) humification of topsoil	Ferm et al. 1992
Scots pine/Finland	5	2 years	3.9 to 5.8	(-) total N in humus (+) base saturation	(+) microbial activity (+) microbial biomass	Fritze et al. 1994
White birch American beech/ Maine	6 13 20	2 years	4.51 to 6.0 4.51 to 6.1 4.51 to 6.2	(+) exchangeable Na, K, SO4, Ca, Mg (-) extractable Fe, Al, Mn (nc) CEC, base saturation	---	Kahl et al. 1996
Scots pine/ Finland	1 2.5 5	4 years	3.8 to 4.4 3.8 to 4.9 3.8 to 5.8	---	(-) microbial biomass (-) ratio of fungi:bacteria	Baath et al. 1994
Scots pine/Finland	16	41 years	4.4 to 6.3	(+) soil nutrients	(+) needle decomposition (+) nutrient cycling	Silfverberg and Hotanen 1989
Red maple/Maine	20	18 weeks	5.0 to 5.3	---	---	Unger and Fernandez 1990
Poplar/ Idaho	0-160	2 months	---	(+) P, K, B availability	---	Etiegni et al. 1991
Loblolly pine/ North Carolina	27	15 months	5.0 to 5.6	(+) Mg, K availability (nc) metals	---	Steponkus 1992

[a] (+) indicates increase; (-) indicates decrease; (nc) indicates no detected effect

Table 2. Summary of reported studies on the effects of biosolids application on the chemical properties and ecology of forest soils.

Species/ Location	Biosolid Application Rate	Total N Equivalent Rate, kg ha^{-1} (% available N, if known)	Study Duration	Soil pH Change	Chemical Change	Ecological Impacts[b]	Source
Willow/ Finland	75 Mg ha^{-1}	300 (8%)	2 years	(nc)	(+) total N (+) denitrification (+) soluble P, Fe (nc) exchangeable K, Mg	(+) cellulose decomposition	Lumme and Laiho 1988
Grand fir Douglas-fir/ Washington	300 Mg ha^{-1}	8000	8 years	5.4 to 4.5	(-) exchangeable Ca, Mg, K (+) exchangeable Al, Fe (+) cation leaching, nitrification	---	Harrison and Henry 1994
Mixed northern hardwoods/ New Hampshire	3.3 Mg ha^{-1} 6.9 Mg ha^{-1} 14.9 Mg ha^{-1}	199 396 740	9 years	3.8 to 4.2 3.8 to 4.1 3.8 to 4.3	(+) N mineralization (+) nitrification	---	Hallett et al. 1999
Lombardy poplar, Douglas-fir, Ponderosa pine/ Washington	500 Mg ha^{-1}	13100	15 years	6.1 to 5.1	(+) C, N, P, Ca, K (+) CEC (nc) Mg	(+) humification (-) fine roots	Harrison et al. 1994
Scots pine/ Scotland	125 m^{3} ha^{-1} 250 m^{3} ha^{-1}	192 (8%)	1 year	---	(+) nitrification (+) Ca, P	---	Ferrier et al. 1996
Mixed northern hardwoods/ New Hampshire	4 Mg ha^{-1} 3yr^{-1}	200 (20–30%)	50 year simulation	---	(+) nitrogen	(+) humus mass	Crohn 1995
Lab incubation/ United Kingdom	40 Mg ha^{-1} 80 Mg ha^{-1} 120 Mg ha^{-1} 160 Mg ha^{-1}	1000 2000 3000 4000	4 weeks	6.5 to 6.4 6.5 to 6.2 6.5 to 6.2 6.5 to 6.2	(-) inorganic N	(-) microbial biomass	Chander et al. 1995
Aspen, Oak, Pine, Mixed northern hardwoods/Michigan	420 g m^{-2} 1020 g m^{-2}	223 (65%) 430 (17%)	8 weeks	(+)	(+) nitrification	(+) nitrifying bacteria	Burton et al. 1990
Sugar maple, beech/ Michigan	15, 672 to 31,350 m^{3} ha^{-}1 yr^{-}	220 (77%)	1 year	---	(+) available P (+) exchangeable Mg (+) Na and Cl	---	Burton and Hook 1979
Red and White pine/ Michigan	4.8 Mg ha^{-1} 9.7 Mg ha^{-1} 19.3 Mg ha^{-1}	287 (28%) 578 (28%) 1160 (28%)	14 months	4.2 to 6.1	(+) nitrate (+) soluble P (nc) Zn, Cu, Cr, Pb, Ni (+) Cd	(nc) bulk density (nc) moisture content	Brockway 1983

(+) indicates increase; (-) indicates decrease; (nc) indicates no detected effect

Table 3. Summary of reported studies of nitrate leaching associated with biosolids applications at a range of total N equivalents.

Site	Amendment	Total N Equivalent Rate, kg ha^{-1} (% available N, if known)	Study Duration	Nitrate Leaching	Source
Sugar maple/ Michigan	Municipal wastewater	220 (77%)	1 year	(+)	Burton and Hook 1979
Pitch pine, oak/ Massachusetts	Municipal wastewater	370-480 (13-19%)	2 years	(++)	Jordan et al. 1997
50-year old Scots pine/ Scotland	Liquid undigested sewage sludge	192 (8%)	1 year	(+)	Ferrier et al. 1996
Northern mixed hardwoods/ New Hampshire	Aerobically digested municipal sewage sludge	199-740	1 year	(++)	Medalie et al. 1994
Sitka spruce/ Scotland	Liquid undigested Sewage sludge	445 (31%) 893 (31%)	5 years	(nc) (nc)	Dutch and Wolstenholme 1994
Northern mixed hardwoods/ New Hampshire	Anaerobically digested sewage sludge	200 (20–30%)	50-year simulation	(nc)	Crohn 1995
Northern mixed hardwoods/ New Hampshire	Dewatered, limed sludge	99 (12%) 477 (12%)	28 months	(nc) (+)	Koterba et al. 1979
Oak and red maple/ Michigan	Liquid anaerobically digested sludge	400	8 months	(+)	Nguyen et al. 1986
Loblolly pine/ southeastern US	Liquid anaerobically digested sludge Solid anaerobically digested sludge	400 (42%) 800 (42%) 630 (2%)	3 years	(+) (++) (+)	Wells et al. 1986

(nc) no significant leaching
(+) significant leaching, but still below EPA standards (10 mg of nitrate L^{-1} soil solution)
(++) leaching exceeds EPA standards for public health

Table 4. Summary of reported studies of nitrate leaching associated with papermill residuals applications at a range of total N equivalents.

Site	Amendment	Total N Equivalent Rate, kg ha^{-1} (% available N, if known)	Nitrate Leaching	Source
Hybrid cottonwood/ Oregon	Primary and secondary papermill residuals	3846	(+)	Shields et al. 1986
Red pine/ Wisconsin	1:1 primary and secondary papermill residuals	550 (<1%) 1120 (<1%) 1670 (<1%)	(++) (++) (++)	Bockheim et al. 1988
Red and white pine/ Michigan.	Papermill residuals	323 578 1156	(nc) (+) (++)	Brockway 1979
Red pine/ Maine	1:1 primary and secondary papermill residuals	200	(+)	Kraske and Fernandez 1993

(nc) no significant leaching
(+) significant leaching, but still below EPA standards (10 mg of nitrate L^{-1} soil solution)
(++) leaching exceeds EPA standards for public health