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# New Municipal Solid Waste Processing Technology Reduces Volume and Provides Beneficial Reuse Applications for Soil Improvement and Dust Control

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## 1. Introduction

The disposal of municipal solid waste (MSW) is an ongoing problem in the United States, and even US Army installations, as a microcosm representing small to medium sized cities across the country, are not immune. The Army generated over 1.2 million metric tons of solid waste in the United States in Fiscal Year 2003 (Solid Waste Annual Reporting, 2003), with a majority shipped to off-post landfills at considerable expense. The US Army Environmental Command has ranked solid waste management as the number one pollution prevention challenge for the Army. Like most cities and towns in the United States and other developed countries, the military is faced with decreasing landfill space, increasing costs of disposal, and mounting environmental pressures for remediation of leaking landfills. The Army operates 16 active landfills that have less than 10 years of useful life, and current landfill costs exceed $140 million annually. These costs are expected to increase dramatically over the next several years with the added pressures of mandated military environmental stewardship and remediation liability for older landfills that have started to leak.

Faced with Executive Order 13101, which dictates Government strategies for waste prevention, recycling, and Federal acquisition policy, and, memorandum DUSD (ES), May 13, 1998, specifying a landfill diversion rate of 40% by 2005, the Government must immediately develop and exploit technologies capable of satisfying these requirements. MSW represents approximately 20% of the total solid waste streams generated by military installations [Waste and Recycling, Jul. 2002]. A major reduction in the amount of this material landfilled contributes significantly, agency-wide, to reaching the goal of Executive Order 13101.

One possible method to relieve this waste problem is to reduce the volume of the municipal solid waste or utilize waste in methods other than landfilling. Collection and composting of organic food, processing, and landscape wastes, as well as paper, glass and metal recycling have made significant contributions to reducing waste volume, but landfill utilization requirements still exceed landfill capacity. Processes and equipment to facilitate the rapid separation, volume reduction, and conversion into reusable products have been developed and tested in limited capacities. This chapter describes one such process developed by

Bouldin and Lawson, Incorporated, which produces a cellulosic by-product, trademarked as Fluff®, which has been shown to be suitable for a number of uses based on laboratory test results that indicate it is relatively benign from an environmental aspect despite the municipal input stream from which it is derived. A full spectrum of research will be presented to highlight (1) the chemical and agronomic nature of this material called Fluff, (2) its mineralization characteristics when used as a soil additive, (3) the effects of land application on vegetative plant growth, development, biomass production, and chemical composition of plant tissues, (4) the effects of land application on numerous soil chemical and physical properties, and (5) results from a proof of concept study showing the applicability of this material for use as a dust suppressant on unpaved roads.

## 2. Fluff: a unique municipal solid waste processing by-product

A solid waste processing technology that facilitates the rapid separation, volume reduction, and conversion of municipal waste into a sterile organic pulp has been developed and deployed at several locations. This process separates the organic fraction of municipal garbage from the recyclable materials and then sterilizes it, producing a pulp-like material called Fluff® (Bouldin & Lawson, Inc., 2000). Raw municipal refuse including paper, glass, metals, plastics, wood, food wastes, vegetative wastes, and other inert materials are introduced into a low-speed, high-torque shredder where the materials are reduced into approximately 2-5 cm square pieces. Batteries, carpet, and any other items that might cause equipment or personnel harm are typically removed by hand from the input stream. The shard pieces produced by the high-torque shredder are delivered to a conveyor system that utilizes magnetic rollers to separate out the ferrous metals. The balance of the waste is then further reduced using a series of smaller shredders and grinders before being conveyed into a hydrolyzer, a jacketed containment vessel using high temperature steam in a proprietary process [US Patent No. 6,017, 475] to break molecular bonds and destroy pathogens (Bouldin & Lawson, Inc., 2000). The resultant hydrolysis product is transferred to an expeller unit (auger) that operates as a "hard" press, serving as a ram to shuttle the moist cellulosic material along an internally tapered tunnel. Water is then removed from the aggregate cellulose in a rotary dryer. The coarse and fine cellulosic mixes are separated from one another through the use of screens and compressed air classification; the lighter, coarser material is deposited in a collection bin while the smaller fractions are tumbled through a rotary drum to remove the fines of aluminum, glass, and plastic, which are gravity-fed into a "particulates" collection bin. The separated fine cellulose material emerges as a sanitized, sand-like granular fluff that is useful as a soil amendment because of its organic base and relatively high nitrogen content. If not utilized as a soil amendment, the Fluff byproduct can still be landfilled at a 30-75% reduction in volume, depending upon input materials (BouldinCorp, unpublished data, 2001). The coarse, peat moss-like material can be extruded into plastic-like composite planks.

This technology is currently in use in Warren County, TN, where a 95% recycling rate has been achieved for the county's municipal solid waste, with the bulk of the organic byproduct composted for use as a topsoil replacement in the horticultural industry (Croxton et al., 2004). Several processing systems have also been deployed in the island countries of Aruba, St. Croix, and St. Thomas, where land fill space is at a premium and alternative Fluff uses include pelleted fuel production and beach erosion prevention and restoration.

Fig. 1. Picture of Fluff material.

## 3. Fluff analysis

The Fluff byproduct has been analyzed for nutrient components important to agriculture and found to have significant nutrient concentrations that could serve as an organic fertilizer source (Table 1) (Busby et al., 2006; Busby, 2003). Fluff has also been intensively analyzed for levels of 184 regulated compounds, including 11 heavy metals, 113 semi-volatile and 60 volatile organic compounds to determine any potential regulatory limitations. Analyses of toxicity characteristic leaching procedure (TCLP) volatiles, TCLP semi-volatiles, TCLP heavy metals, TOX (total organic halogen content), and low resolution dioxin content were performed by PDC Laboratories (Peoria, IL), a United States Environmental Protection Agency (EPA) certified laboratory for Tennessee, using EPA methods SW846-8260, 8270, 1311, 9076, and 8280, respectively (USEPA 1998). Only 9 heavy metals, 3 semi-volatile and 3 volatile organic compounds were detected. The detected organic compounds [acetone, methylene chloride, toluene, di(2-ethylhexyl)phthalate, di-n-butyl phthalate, and di-n-octyl phthalate] are regulated in either the Clean Water Act or the Clean Air Act due to risks associated with workplace exposure and concentrated industrial effluent. However, due to their volatile chemical nature and rapid turnover in the environment, they pose very little risk at concentrations found in the Fluff, especially when incorporated into the topsoil, and therefore are not regulated for this purpose.

Limits have been established for land application of heavy metals in biosolids and these existing standards were used to assess metal loading of Fluff in the absence of a similar compost standard (40 C.F.R. Part 503, 1999). A comparison of Fluff heavy metal concentrations and EPA biosolids limits for maximum metal concentrations, maximum annual soil metal loading, and maximum cumulative soil metal loading are presented in Table 2. In comparing metal concentrations in Fluff to the biosolids ceiling limits, it was found that all Fluff metal concentrations were at least an order of magnitude below their respective ceiling limits. The Fluff metal concentrations were used to calculate maximum annual and cumulative application rates, where lead (Pb) was found to be the contaminant of primary concern. Annually, this limit would be reached with an application rate of 229

Mg ha$^{-1}$. The maximum cumulative Fluff application rate was found to be 4587 Mg ha$^{-1}$, or 20 repeated applications at the maximum annual limit. However, other factors would most likely preclude achieving these rates due to material and land availability, transportation, and effective soil incorporation constraints. Agriculturally significant properties of the Fluff are presented in Table 1. Fluff has a near-neutral pH a C:N ratio around 30, and research indicates it decomposes slowly (Busby et al., 2007).

| | |
|---|---|
| pH | 6.5 |
| C:N | 32 |
| C (%) | 39.8 |
| N (%) | 1.26 |
| P (mg kg$^{-1}$) | 1900 |
| K (mg kg$^{-1}$) | 2170 |
| Ca (mg kg$^{-1}$) | 13600 |
| Mg (mg kg$^{-1}$) | 1400 |
| Fe (mg kg$^{-1}$) | 2460 |
| Mn (mg kg$^{-1}$) | 130 |
| Zn (mg kg$^{-1}$) | 234 |
| B (mg kg$^{-1}$) | 35 |
| Cu (mg kg$^{-1}$) | 47.7 |
| Co (mg kg$^{-1}$) | 2.0 |
| Na (mg kg$^{-1}$) | 5169 |

Table 1. Fluff properties significant to agriculture.

### 3.1 Fluff C mineralization analysis

A key component of this new municipal solid waste processing technology is that Fluff can be utilized as a soil amendment to improve soil physical and chemical condition. Since most contaminants and pathogens are removed through the processing technology, Fluff could bypass the composting process and eliminate the most negative aspects of large-scale composting: the time, facilities infrastructure, and resulting management costs as well as the associated problems with leachate, odors, pests, and pathogen exposure (Busby et al., 2003). However, non-composted materials are generally not used because undecomposed organic matter is often attributed to phytotoxic effects and nutrient immobilization when applied to soil (Edwards, 1997; Zucconi et al., 1981a; Chanyasak et al., 1983a,b; Wong, 1985; Bengston and Cornette, 1973; Terman et al., 1973).

When applying organic materials such as municipal waste compost to soil, care must be taken not to adversely affect the establishment and growth of vegetation. Undecomposed compost that is high in $NH_4$, organic acids, and other compounds can be phytotoxic (Zucconi et al., 1981b; Chanyasak et al., 1983a,b; Wong, 1985). Fortunately, these chemicals most often occur for short durations and do not induce lasting toxic effects in the environment (Zucconi et al., 1981a). Longer term effects can occur from unstabilized organic material with a high C:N ratio, as microbial decomposition can immobilize significant amounts of N, making it unavailable for plant utilization and leading to deficiency problems (Bengston and Cornette, 1973; Terman et al., 1973). Composting organic matter will alleviate these potential problems, but only if the substrate is allowed to compost to maturity.

| Metal | Fluff (mg kg$^{-1}$) | Biosolids Ceiling Limits (mg kg$^{-1}$)[2] | Biosolids Annual. Loading Rate Limits (kg ha$^{-1}$ yr$^{-1}$)[3] | Calculated Maximum Annual Fluff Application Rate (Mg ha$^{-1}$ yr$^{-1}$) | Biosolids Cumulative Loading Limits (kg ha$^{-1}$)[4] | Calculated Maximum Cumulative Fluff Application (Mg ha$^{-1}$) |
|---|---|---|---|---|---|---|
| As | <RL[1] | 75 | 2 | - | 41 | - |
| Ba | 46.6 | - | - | - | - | - |
| Cd | 1.9 | 85 | 1.9 | 1000 | 39 | 20526 |
| Cr | 39.8 | - | - | - | - | - |
| Cu | 47.7 | 4300 | 75 | 1572 | 1500 | 31447 |
| Hg | 0.547 | 57 | 0.85 | 1554 | 17 | 31079 |
| Ni | 9.12 | 420 | 21 | 2303 | 420 | 46053 |
| Pb | 65.4 | 840 | 15 | 229 | 300 | 4587 |
| Se | 9.67 | 100 | 5 | 517 | 100 | 10341 |
| Zn | 234 | 7500 | 140 | 598 | 2800 | 11966 |

[1] Reaction Limit; [2]from 40 CFR Part 503.13, Table 1; [3]from 40 CFR Part 503.13 Table 4; [4]from 40 CFR Part 503.13 Table 2

Table 2. Comparison of fluff heavy metal concentrations with USEPA limits for biosolids application.

To date, there is no agreed upon test to determine whether or not compost is mature, or even what the definition of mature should be. Numerous tests and measurements have been developed to provide insight into changes that occur in decomposing organic matter, how these changes relate to maturity, and how these changes might affect plant growth (Jimenez and Garcia, 1989; Bernal et al., 1998; Cooperband et al., 2003). The general consensus is that a series of tests, encompassing several different aspects of decomposition, is the most reliable method of determining compost maturity. Two validated, simple, and widely used tests to predict the maturity of composting organic matter are the C evolution and N mineralization tests. When combined, these tests can provide good indications of when a decomposing material may be phytotoxic, immobilizing nutrients, or mature by combining measurements of microbial respiration with $NO_3$ and $NH_4$ concentrations.

Utilization of non-composted waste material such as Fluff provides significant benefits over handling costs associated with composting. However, because this municipal waste product is unstabilized, there were concerns regarding the effect microbial decomposition of this material has on nutrient availability when used as a soil amendment. Therefore, studies were conducted to determine the rate of decomposition and N cycling of Fluff at increasing rates in two distinct sandy soils and comparing them to mature commercial municipal waste compost (Busby et al., 2007).

In the Busby et al. (2007) study, a 90 d incubation was performed to measure C and N mineralization of composted and un-composted municipal wastes at varying rates. Total C and N of both organic additives were analyzed and indicated that Fluff had a much higher C content but similar nitrogen concentration compared to the compost (Table 3).

| | Fluff[1] | MWC[2] |
|---|---|---|
| pH | 6.5 | 7.1 |
| C:N | 32 | 12.9 |
| C (%) | 37.1 | 16.5 |
| N (%) | 1.26 | 1.25 |
| P (mg kg$^{-1}$) | 1900 | 3880 |
| K (mg kg$^{-1}$) | 2170 | 7070 |
| As (mg kg$^{-1}$) | <RL | 12.2 |
| Cd (mg kg$^{-1}$) | 1.9 | 7.76 |
| Cu (mg kg$^{-1}$) | 47.7 | 811.8 |
| Ni (mg kg$^{-1}$) | 9.12 | 67.2 |
| Pb (mg kg$^{-1}$) | 65.4 | 447.5 |
| Se (mg kg$^{-1}$) | 9.67 | 1.25 |
| Zn (mg kg$^{-1}$) | 234 | 1692 |

[1]Fluff = Un-composted municipal waste; [2]MWC= Municipal waste compost

Table 3. Chemical properties of organic additives.

Two soils were collected from study sites at Fort Benning, GA: a Troup loamy fine sand (Loamy, kaolinitic, thermic Grossarenic Kandiudults) designated "Dove Field" and a highly disturbed Orangeburg loamy sand (Fine-loamy, kaolinitic, thermic Typic Kandiudults) designated "Borrow Pit" to use in the incubation (Soil Series Classification Database, 2008). Methods of incubation followed techniques described by Torbert et al. (1998). Treatments consisted of 25 g dry weight of sieved soil samples placed in small plastic cups. Composted (MWC) or un-composted municipal waste (Fluff) was mixed into soils at desired application rates, and deionized water was added to moisten soils to 85% of field capacity. Cups were then placed in 1.06 l jars which were fitted with $CO_2$ traps and incubated in the dark at 25°C and 70% relative humidity for 90 d. Soil samples were extracted every 30 d and analyzed for $NH_4$ and $NO_3$. Percent of additive total organic carbon (TOC) mineralized was also determined by subtracting the evolved C for each control soil from each respective experimental unit and dividing the net additive C evolved by the TOC added by each respective additive-rate treatment.

Carbon mineralization of the Fluff was much higher than in the mature compost (Table 4). The higher rates of Fluff application still had significantly higher C evolution rates than the compost even after 90 d of incubation, indicating that this material was still not completely stabilized at a level similar to that of the compost. Further, the percent added TOC mineralized indicates that the compost was much more stable, although the percent Fluff TOC mineralized in the Dove Field soil did stabilize after 60 d (Table 5). Soil type heavily influenced C evolution of the decomposing Fluff, as the soil with higher initial C and N concentrations had significantly higher rates of C evolution across application rates. This difference was most likely due to the differences in available soil N, as the N was extremely limited in the Borrow Pit soil and slightly less so in the Dove Field soil, which could have significantly reduced microbial activity. This is further demonstrated by the inverse relationship between Fluff application rate and percent TOC mineralized in the Dove Field soil, as the N limitation would have increased with increasing Fluff application.

| | mg CO2-C kg$^{-1}$ soil$^{-1}$ d$^{-1}$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Dove Field Soil | | | | | | | |
| | 17.9 Mg ha$^{-1}$ | | 35.8 Mg ha$^{-1}$ | | 71.6 Mg ha$^{-1}$ | | 143 Mg ha$^{-1}$ | |
| Day | Fluff* | MWC** | Fluff | MWC | Fluff | MWC | Fluff | MWC |
| 30 | 24.74 | 3.50 | 34.02 | 4.20 | 56.12 | 6.65 | 80.85 | 9.81 |
| 60 | 9.94 | 0.53 | 17.76 | 1.93 | 24.74 | 1.93 | 35.10 | 2.98 |
| 90 | 5.98 | 1.58 | 9.64 | 2.10 | 13.97 | 2.45 | 17.63 | 4.90 |
| | Borrow Pit Soil | | | | | | | |
| | 17.9 Mg ha$^{-1}$ | | 35.8 Mg ha$^{-1}$ | | 71.6 Mg ha$^{-1}$ | | 143 Mg ha$^{-1}$ | |
| Day | Fluff | MWC | Fluff | MWC | Fluff | MWC | Fluff | MWC |
| 30 | 8.72 | 2.80 | 21.54 | 2.80 | 36.30 | 4.90 | 76.08 | 7.71 |
| 60 | 4.22 | 1.05 | 6.61 | 2.10 | 13.57 | 0.18 | 26.39 | 2.63 |
| 90 | 0.11 | 0.00 | 3.07 | 0.00 | 4.65 | 2.28 | 16.85 | 3.68 |

* Fluff = Un-composted municipal waste
** MWC = Municipal waste compost

Table 4. Comparison of carbon evolution rates between soils, additives, rates, and incubation duration.

Total inorganic N and $NO_3$ levels were considerably higher in the compost treatments than in the Fluff treatments, indicating that decomposition of the Fluff resulted in significant N immobilization (Table 6). No changes in inorganic N concentration were observed in the Borrow Pit Fluff treatments through 90 d, but the Dove Field Fluff treatments did increase slightly over time, with an inverse relationship between rate and inorganic N concentration after 90 d of incubation. Ammonia levels did not differ at the same magnitude. Ammonia concentrations in the compost treatments remained very low and relatively constant across rates and soils but decreased slightly over time. Ammonia concentrations in the Dove Field

| | % C mineralized of additive TOC | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Dove Field | | | | | | | |
| | 17.9 Mg ha$^{-1}$ | | 35.8 Mg ha$^{-1}$ | | 71.6 Mg ha$^{-1}$ | | 143 Mg ha$^{-1}$ | |
| Day | Fluff* | MWC** | Fluff | MWC | Fluff | MWC | Fluff | MWC |
| 30 | 15.45 | 1.06 | 11.68 | 1.14 | 9.58 | 1.49 | 7.43 | 1.41 |
| 60 | 26.71 | 1.71 | 19.27 | 2.55 | 15.06 | 2.19 | 11.31 | 2.00 |
| 90 | 25.85 | 3.30 | 19.86 | 3.06 | 17.83 | 2.65 | 12.36 | 2.64 |
| | Borrow Pit | | | | | | | |
| | 17.9 Mg ha$^{-1}$ | | 35.8 Mg ha$^{-1}$ | | 71.6 Mg ha$^{-1}$ | | 143 Mg ha$^{-1}$ | |
| Day | Fluff | MWC | Fluff | MWC | Fluff | MWC | Fluff | MWC |
| 30 | 4.78 | 0.94 | 6.46 | 0.54 | 6.02 | 1.13 | 6.47 | 1.04 |
| 60 | 9.70 | 2.18 | 10.32 | 2.07 | 9.22 | 1.16 | 9.16 | 1.51 |
| 90 | 8.91 | 2.18 | 11.32 | 2.07 | 10.29 | 2.07 | 10.34 | 2.23 |

* Fluff = Un-composted municipal waste; ** MWC = Municipal waste compost

Table 5. Comparison of percent carbon mineralization of additive total organic carbon (TOC) between soils, additives, rates and incubation duration.

Fluff treatments peaked at day 60 and decreased to their initial levels by day 90, indicating that net ammonification had occurred during the incubation but net nitrification had begun by the end of the 90 d. Even at the peak, however, $NH_4$ levels still remained at low concentrations (<11 mg kg$^{-1}$). The low concentrations of $NH_4$ indicate that potential toxicity from $NH_4$ buildup would not be a problem in these soils even at rates of 143 Mg ha$^{-1}$. In the Borrow Pit soil, neither net ammonification nor nitrification was ever indicated throughout the incubation as both $NH_4$ and $NO_3$ concentrations stayed consistently low. This consistency indicates a severe N deficiency in this soil and was probably responsible for the slower decomposition of the Fluff.

| | Total Inorganic N Concentration (mg kg$^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Dove Field Soil | | | | | | | |
| | 17.9 Mg ha$^{-1}$ | | 35.8 Mg ha$^{-1}$ | | 71.6 Mg ha$^{-1}$ | | 143 Mg ha$^{-1}$ | |
| Day | Fluff* | MWC** | Fluff | MWC | Fluff | MWC | Fluff | MWC |
| 30 | 2.60 | 38.54 | 3.71 | 59.65 | 4.17 | 85.22 | 3.778 | 117.68 |
| 60 | 14.89 | 51.80 | 12.16 | 67.34 | 10.13 | 108.06 | 6.586 | 139.94 |
| 90 | 22.93 | 56.12 | 15.35 | 68.78 | 7.47 | 101.57 | 5.218 | 132.688 |
| | Borrow Pit Soil | | | | | | | |
| | 17.9 Mg ha$^{-1}$ | | 35.8 Mg ha$^{-1}$ | | 71.6 Mg ha$^{-1}$ | | 143 Mg ha$^{-1}$ | |
| Day | Fluff | MWC | Fluff | MWC | Fluff | MWC | Fluff | MWC |
| 30 | 0.00 | 18.54 | 0.00 | 29.11 | 0.00 | 55.93 | 0.50 | 112.92 |
| 60 | 0.40 | 17.30 | 0.93 | 30.61 | 1.08 | 64.55 | 1.01 | 123.58 |
| 90 | 0.00 | 14.64 | 0.30 | 31.68 | 0.11 | 61.86 | 0.63 | 123.79 |

* Fluff = Un-composted municipal waste; ** MWC = Municipal waste compost

Table 6. Differences in total inorganic nitrogen concentration between soils, additives, rates, and incubation duration.

Because both soils were relatively infertile and both C and N mineralization of the Fluff were closely tied to the fertility status of the soils, it is likely that Fluff decomposition will occur at a faster rate in more fertile soils. When used in infertile soils, N immobilization will occur for an extended period due to incorporation into microbial biomass, with potential negative consequences for vegetation initially, but fertilization with a readily available N source may alleviate the period of this immobilization. On the other hand, slower degradation of the material may provide the best long term benefit as leaching losses would be minimized and N inputs would more closely resemble natural soils, as was found with yard waste compost that led to net immobilization initially (Claassen and Carey, 2004). For vegetation that requires significant N inputs, the mature compost would work well as it provided a steady and significant amount of N throughout the 90 d. In settings where available N could be detrimental, such as native plant restorations or in other instances where weed pressure is undesirable and detrimental, Fluff application could be a simple way to decrease available N in the short term, but would most likely provide a slowly available source over the longer term. Restoration of late-seral plant communities has previously been achieved through high C:N organic soil amendments such as sucrose and sawdust that limit available N (McLendon and Redente, 1992; Morgan, 1994; Paschke et al., 2000). Additionally, any increase in the organic C content of soil can provide significant benefits, especially in degraded soils where vegetative cover is minimal. Soil organic matter reduces compactibility (Zhang et al., 1997), increases water holding capacity (Hudson, 1994), increases particle aggregation (McDowell and Sharpley, 2003), and reduces erodibility (Gilley and Risse, 2000; Barthes et al., 1999).

The comparison between these data and other studies using raw household waste (Bernal et al., 1998) indicates that the MWC used here had a much lower rate of C mineralization relative to the unprocessed waste in the previous study, with the only major difference between the organic materials being the processing technology used to produce MWC. Because the MWC had such a low rate of C mineralization relative to the raw waste, the processing must have a significant effect on the material's degradation rate. If the carbonaceous material resulting from this process increases the residence time of added C in soil, this could be a significant benefit for increasing organic matter in soils. The increase in soil C and decrease in soil N from the un-composted Fluff indicates that it would be best suited for highly degraded soils where establishment of native perennial communities adapted to N limitation is desired.

## 4. Fluff uses

This waste processing technology is currently in use in Warren County, TN, where a 95% recycling rate has been achieved for the county's municipal waste, with the bulk of the organic byproduct composted for use as topsoil replacement in the horticultural industry (Croxton et al., 2004). While the resulting Fluff material has been used successfully after composting in the horticulture industry, Fluff may also be an effective soil amendment before composting to improve soil physical and chemical properties, thereby enhancing land rehabilitation efforts. The Fluff is unique in both origin and physical attributes when compared to other soil amendments, and land application studies have recently been conducted by the US Army Corps of Engineers to improve Army training ground rehabilitation, based on results of the incubation studies described above. The United States Army generated over 1.2 million metric tons of solid waste in the United States in Fiscal Year 2003 but has a limited number of landfills, increasing costs to ship garbage off post (Solid Waste Annual Reporting, 2004). However, with almost 5 million hectares of land in the United States, including 73 installations with greater than 4,000 hectares each, the Army has enough acreage to support large-scale land utilization of organic waste byproducts (DoD, 2001). Large blocks of this land are in need of rehabilitation due to historic and contemporary Army training activities, but often lack sufficient topsoil, organic matter, and nutrients required for successful rehabilitation. By diverting organic matter from landfills to degraded training lands, the Army could incorporate reuse of municipal waste into land management, decrease waste disposal costs, and improve land rehabilitation efforts on Army training and testing ranges.

Due to the expenses involved with overcoming these land rehabilitation limitations, a cheap alternative material is needed. An effort to utilize organic waste byproducts by the Army could be greatly enhanced if the need for large scale composting facilities for municipal waste could be eliminated. The use of a highly processed organic pulp such as Fluff could divert organic matter from landfills to degraded training lands. On marginal lands such as degraded training areas, organic amendments such as Fluff can be beneficial when used to enhance vegetation establishment. The increased soil organic matter should increase the soil water holding capacity and pH, lower soil bulk density, and provide a slowly available source of nutrients. Studies were conducted to test the hypothesis that an undecomposed material such as Fluff is beneficial as an organic soil amendment that can aid in the establishment of native grasses. While many similarities exist between the land application of other agricultural and industrial waste products such as poultry litters, animal manures (Karlen et al., 1998), and composted biosolids, Fluff is a unique byproduct which required experimental studies to understand the impacts to vegetative establishment, plant nutrient status and impacts to soil quality.

### 4.1 Land application and vegetation establishment

As previously noted, a potential problem with non-composted organic material is the high C:N ratio, which could create a soil environment with low N availability. However, the creation of low N availability may be an advantage for establishing native vegetation that is adapted to nutrient limited soils and would benefit greatly from a reduction in weed competition for N (Paschke et al., 2000; Barbour et al., 1999; Wilson and Gerry, 1995; McLendon and Redente, 1992). Perennial warm season grasses, such as those native to the Tallgrass Prairie of North America, are well adapted to harsh environmental conditions, including low N availability, giving them a competitive advantage in poor soils (Jung et al., 1988; Wilson and Gerry, 1995; Skeel and Gibson, 1996; Levy et al., 1999). These grasses are used abundantly in reclamation, as they develop extensive root systems that penetrate deep into soils, providing a very effective safeguard against erosion (Drake, 1983). Although these species are highly suited to conservation planting, establishment is a significant barrier to successful utilization, as weedy species can easily overtake them and cause failure, especially in N rich soils (Launchbaugh, 1962; Wedin and Tilman, 1993, 1996; Munshower, 1994; Warnes and Newell, 1998; Reever and Seastedt, 1999; Brejda, 2000).

Studies have been conducted to evaluate the use of Fluff as a soil amendment to successfully rehabilitate damaged military training lands, which often lack sufficient topsoil, organic matter, and nutrients required for successful rehabilitation (Busby et al., 2006; Busby et al., 2010). Busby et al. (2010) carried out a field study in North-Central Tennessee at the Fort Campbell Military Reservation, on an abandoned hay field currently used for Army training activities. Soil at the site was a Sengtown silt loam (fine, mixed, semiactive, thermic, Typic Paleudalfs) (Soil Survey of Montgomery County, Tennessee, 1975). Application of Fluff was made at rates varying from 0 to 36 Mg ha$^{-1}$. Three warm season grasses species (Big Bluestem - *Andropogon gerardii* , Switchgrass - *Panicum virgatum*, and Indiangrass - *Sorghastrum nutans*) and one cool season grass (Virginia Wildrye - *Elymus virginicus*) were planted. In a separate study, two sites on Fort Benning Military Reservation, GA, were established. The sites chosen were designated as "Dove Field" [a moderately degraded Troup sandy loam soil] and as "Borrow Pit" [highly degraded Borrow Pit soil (highly disturbed Orangeburg Fine-loamy soil (Soil Survey of Muscogee County, Georgia, 1983) (Fig. 2). At these sites, treatment plots consisted of a control where nothing was done, a control with revegetation only, and application of Fluff at rates varying from 0 to143 Mg ha$^{-1}$ with revegetation. As in Tennessee, native grasses Big Bluestem, Switchgrass, Indiangrass, and Virginia Wildrye were planted. Vegetation sampling, including plant biomass (Bonham, 1983), plant nutrient composition, plant species composition (Sharrow and Tober, 1979) and basal vegetative cover, were measured at the end of each of two growing seasons. Plant biomass was collected, consisting of composite samples of all species present. Analysis was performed for total Carbon (C), nitrogen (N), aluminum (Al), boron (B), barium (Ba), calcium (Ca), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), phosphorus (P), lead (Pb), silicon (Si), and zinc (Zn).

### 4.2 Vegetation growth and composition

At the Fort Campbell experimental sites, vegetation consisted primarily of agricultural grasses and forbs typical of early successional communities with 49 species in 24 families recorded for the entire study area. After two growing seasons following Fluff application and seeding with the desired warm and cool season grasses, total basal vegetative cover differences were not significant across years or treatments. Annual grass and total annual cover were relatively unaffected by Fluff treatment but were significantly higher in the unseeded control treatment than in the 36 Mg ha$^{-1}$ treatment. The 36 Mg ha$^{-1}$ treatment had significantly higher total perennial, perennial grass, and planted grass cover than both the seeded and unseeded controls. Big bluestem, indiangrass, and switchgrass cover were unaffected by treatment.

Based on the results of the species composition and basal cover analyses, establishment of 2 of the 3 native warm season prairie grasses was enhanced with pulp application rates of 36 Mg ha$^{-1}$. Indiangrass appears to be relatively unresponsive to the Fluff, but switchgrass and big bluestem showed notable density and cover increases at the highest application rate.

Fig. 2. Borrow Pit field sites on Fort Benning Military Reservation, GA; A) initial application of Fluff, B) plant growth after 2 years.

No differences in biomass were found between the Fluff treatments and seeded control. The lack of change in biomass in the unseeded control plots compared to the seeded plots was most likely due to dominance by ruderal species in the unseeded control plots that typically lack the biomass found in the seeded perennial grasses. Because annual grass cover remained constant but its relative percent composition decreased, it can be concluded that the Fluff was in some way beneficial to the prairie grasses but not inhibitory to weedy species during the first 2 growing seasons following application of up to 36 Mg ha$^{-1}$. This would be expected for sites with relatively good soil fertility such as those seen at the Fort Campbell experimental sites.

At Fort Benning, a total of 21 species were sampled in the research plots over 2 years. Combined, planted grass species comprised 98.2% of the total species composition of the Borrow Pit and 87.3% of the Dove Field. Application rate had no effect on percent composition of total planted grasses at either site. Switchgrass appeared to be the best suited species as it dominated all seeded sites and comprised the highest relative percentage composition and basal cover of all species present (Fig. 2). It also responded most favorably to Fluff application as basal cover increased significantly with increasing application rate at both sites. Additionally, switchgrass performed so well that the majority of plants produced seed during the first growing season at both sites, which may have contributed to increased dominance the following year. Big bluestem appeared to be unaffected by application rate at the Dove Field site, but basal cover increased significantly with increasing application rate at the Borrow Pit. Given that the more fertile Dove Field site was more conducive to vegetation establishment than the Borrow Pit, this may have been the result of oversupplying nutrients at high application rates which big bluestem was not able to fully exploit at the Dove Field. However, higher application rates overcame deficiencies and created more favorable growing conditions at the Borrow Pit which positively influenced big bluestem growth.

Indiangrass initially performed well in the Dove Field, but remained only a minor vegetation component at the Borrow Pit. Given that indiangrass diminished over time and in response to increased Fluff, while the other two dominant species increased, it appears that indiangrass was not able to effectively compete with switchgrass and big bluestem at either site in the presence of Fluff amended soil. Indiangrass high relative composition in the controls indicates that it was competitive in unamended soils, but its low relative composition in the higher application rates indicates that it was not able to effectively exploit any benefits provided by the amended soils in the manner observed by switchgrass. Further, because it was so much more prevalent in the Dove Field than in the Borrow Pit, indiangrass was not as tolerant to the highly unfavorable growing conditions in the Borrow Pit as were the other species.

Biomass was much higher in the Dove Field than in the Borrow Pit across application rates, but both sites responded very well to increased Fluff application (Table 7). In the Dove Field, biomass remained relatively constant in the unseeded control at less than 300 g $m^{-2}$ but almost doubled in the 143 Mg $ha^{-1}$ treatment from 539 to 1059 g $m^{-2}$ from 2003 to 2004. In the Borrow Pit, the unseeded control lacked any biomass throughout the study, but the 143 Mg $ha^{-1}$ treatment increased from 345 to 582 g $m^{-2}$ over time.

| Fluff Rate | Dove Field | | Borrow Pit | |
|---|---|---|---|---|
| | 2003 | 2004 | 2003 | 2004 |
| Mg $ha^{-1}$ | ------------------- (g $m^{-2}$) ---------------------- | | | |
| Unseeded Control | 243 | 291 | 0 | 0 |
| 0 | 269 | 392 | 18 | 14 |
| 18 | 344 | 617 | 46 | 90 |
| 64 | 428 | 613 | 73 | 122 |
| 72 | 468 | 749 | 202 | 403 |
| 143 | 539 | 1059 | 345 | 582 |

Table 7. Biomass yields as affected by Fluff application for the Dove Field and Borrow Pit study sites in 2003 and 2004.

Weedy annual grasses were not affected at the level originally hypothesized. It was expected that annual weeds, with characteristic shallow root systems and intolerance to shading, would respond negatively to increased competition with taller, deeper rooted perennial prairie grasses. Even though annual grasses were unaffected, the increases in switchgrass and big bluestem cover show a positive result of pulp application. Because the planted grass species constituted almost all vegetation that was sampled in the seeded plots (98% in the Borrow Pit and 87% in the Dove Field) and resulted in mean basal cover values of 7.5% and 12.2%, respectively, establishment of a native grass community was considered successful at both sites.

### 4.3 Plant chemical analysis

Plant chemical composition was also measured to monitor potential changes in plant uptake patterns due to Fluff additions. The measurements were made not only to determine potential changes in the plant health by measuring plant nutrient concentration, but also to measure the potential for environmental concerns with the uptake of heavy metals. In the silt loam soils in Tennessee, soil concentrations of many metals and nutrients were unaffected by Fluff addition, but plant P and Pb accumulation was increased by the 36 Mg ha$^{-1}$ treatment. However, the increase in Pb was insignificant (1.5 mg kg$^{-1}$ for the highest Fluff rate) with respect to established regulatory limits. The increase in soil P concentrations in the high pulp rates alleviated an apparent P deficiency in the study site soils.

Based on these findings, it would be beneficial to use this material as a soil amendment for reestablishing perennial warm-season grasses on disturbed acidic soils with limited P availability. Rates of at least 36 Mg ha$^{-1}$ should be used to achieve noticeable benefits to seeded species, although the upper limit for these benefits has not been determined. The annual limit of Fluff application from a regulatory standpoint based solely on levels of Pb in the material compared to allowable levels in biosolids application would be approximately 230 Mg ha$^{-1}$ year$^{-1}$, with a cumulative limit attained near 4600 Mg ha$^{-1}$. However, due to logistical challenges and the potentially negative effects on soil physical and chemical properties, these rates would not be advisable. If the highest application rate used in this study were repeated once every five years, the limit would be reached in about 650 years. However, to maintain native grass stands, the annual application rate would be significantly lower due to potential negative compositional changes that could result from nitrogen deposition over time.

In the sandy soils at Ft. Benning, more distinct differences were observed with the increasing rates of Fluff. Plant nutrition was improved at both sites, however, due to very distinctive soils between sites, the effects were dissimilar. At the more productive Dove Field site, plant N, P, K, and Na concentrations increased with increasing Fluff application. At the highly disturbed Borrow Pit site, plant P and Na concentrations also increased with increasing Fluff, as well as Mg concentration. An apparent Fe toxicity problem at the highly degraded site was alleviated by high applications of Fluff, as the control plots and lower application rate treatments accumulated extremely high levels of plant Fe. Plant Ba concentration was also reduced by increasing application of Fluff at both sites. The improved plant nutrition and improvements in cover and biomass of perennial native vegetation at both sites indicates an undecomposed organic material such as Fluff can positively influence the establishment of native vegetation in disturbed soils with highly variable properties. Results indicate that greater benefits are achieved with higher levels of soil degradation when using fluff to aid in establishment of warm-season prairie grasses.

### 4.4 Impacts on soil

An important consideration in the utilization of Fluff as a soil amendment is what impact it might have on soil condition or quality. To examine the potential impact on soil chemical and physical conditions, soil samples (Prior, et al., 2004) were collected following the application of Fluff on degraded US Army training grounds in both sandy loam and silt loam soils (Torbert et al., 2007; Busby et al., 2010). Soil samples were obtained at depths of 0-5, 5-10, 10-20, and 20-30, 30-60 and 60-90 cm and analyzed for total N and C, nitrate, and ammonia (Nelson and Sommers, 1996). Extractable Al, As, B, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, S, Se, and Zn concentrations as well as soil pH and bulk density were also determined (Bremmer, 1996; Soltanpour et al., 1996; Hue and Evans, 1986).

### 4.4.1 Silty-loam soils

For silty loam soils, few treatment effects were found for soil nutrients analyzed. Soil C and P concentration was higher with 36 Mg $ha^{-1}$ fluff application than in the unseeded control, but soil N was unaffected by Fluff application. Impacts were also noted for soil K, Ca, Mn, and Cu with Fluff application. Few differences were observed for soil heavy metals, but Fluff application did impact Pb, Al, and As when extracted with Mehlich III extractant (Mehlich, 1984). Mean As concentrations were lower in the Fluff treatments than the unseeded control, and Pb concentration increased approximately 1.5 mg $kg^{-1}$ in the 36 Mg $ha^{-1}$ treatment over the controls.

The analysis of soil chemical properties indicated that Fluff application can significantly increase available P in soils. The increase in extractable soil P in the highest application rates combined with a stable and sufficient level of plant P indicated that an adequate amount of labile P was supplied by Fluff rates greater than 18 Mg $ha^{-1}$ in this silt loam soil. Whether the effect of increased plant P accumulation is a direct result of Fluff supplied P or by some other mechanism is unknown. Because weedy plants usually respond better to fertilization than warm season prairie grasses, this result may have been due to increased mycorrhizal infectivity as weedy grasses did not diminish with increasing application rate, but prairie grasses increased (Noyd et al., 1995, 1996). However, given that soil P levels only increased in the depths where Fluff was incorporated, decomposition of the Fluff and subsequent mineralization of P was most likely responsible. The added P from Fluff may have promoted N immobilization, which would affect annual species more than the planted perennial grasses, as the prairie grasses are much more efficient at nutrient utilization (Brejda, 2000). This would explain why plant shoot P concentration, soil P concentration, cover of planted grasses, and Fluff application rate were all directly related, but soil and shoot N concentrations and annual grass cover were unaffected.

Although soil Pb levels increased significantly from a statistical standpoint in the upper profiles at high Fluff rates, there was no significant change from a regulatory standpoint: amounting to a net increase of approximately 1.5 mg $kg^{-1}$ in the top 30 cm of the soil profile at the highest Fluff application rate. Additionally, both P and Pb only increased in the top 10 cm where the Fluff was incorporated, indicating that no movement into the lower soil profile was occurring after 2 growing seasons. Because Pb is very tightly bound by soil organic matter, it does not readily leach through the soil profile and is largely unavailable for plant uptake (Kabata-Pendias, 2001).

### 4.4.2 Sandy-loam soils

In sandy loam soils (Torbert et al., 2007), the addition of Fluff had an impact on the soil bulk density level in the surface soil (0-5 cm). While no significant difference was noted for depths below 0-5 cm at either study site, the impact of improving the soil bulk density in the soil surface would be important for soil quality and native grass establishment. At the Dove

Field, the soil bulk density was in the range of 1.56 g $cm^{-3}$ at the initiation of the study, but with the application of 143 Mg $ha^{-1}$ Fluff, soil bulk density was drastically reduced to 1.17 g $cm^{-3}$. An even larger impact was observed with the soil at the Borrow Pit site, where the initial level of soil bulk density was 1.83 g $cm^{-3}$. The addition of Fluff at this site reduced the soil bulk density to 1.22 g $cm^{-3}$ with application rates of 143 Mg $ha^{-1}$.

The level of reduction observed with Fluff application would have an important impact on soil condition at both locations. Soil bulk densities above 1.5 g $cm^{-3}$ have generally been shown to be detrimental to root growth and plant yield (Gliski and Lipiec, 1990). The reduction in the level of bulk density observed in this first year would be much more conducive to both plant establishment and root growth of the native grasses. The soil bulk density levels observed from second year soil sampling indicated that the soil physical condition had been substantially improved and that this improvement would likely persist. The improvement in soil bulk density alone would indicate that the degraded soil conditions commonly associated with US Army training activities could be substantially ameliorated with high Fluff application rates.

The ability of the soil to provide plant nutrients is controlled by many factors, such as organic matter content, soil pH, and soil texture (Potash and Phosphate Inst., 2003; Mengel and Kirkby, 1982). Many of these factors, such as soil organic matter content, are reduced in degraded soils, thereby reducing the ability of the soil to provide adequate plant nutrient supply. As noted, the Fluff contained substantial amounts of essential plant nutrients, which would have been present with the application of the Fluff (Table 1). However, these nutrients would not necessarily be available for plant uptake, depending on the condition of the soil, particularly the soil pH level, and the decomposition and release of the nutrients in the Fluff (Potash and Phosphate Inst., 2003).

Extractable soil nutrients (Mehlich, 1984), measured at the end of the first growing season for both sites, are shown in Table 8**.** The application of Fluff increased extractable nutrients in the surface soil layer at both sites. At the Dove Field, a less degraded soil compared to the Borrow Pit, Fluff application resulted in a significant impact on P, B, Ca, Co, and Zn. The soil concentration of Ca and P were particularly improved with the application of Fluff, with Ca concentrations increasing from 195 to 1835 mg $kg^{-1}$ and P concentrations increasing from 29 to 145 mg $kg^{-1}$ with the application of 143 Mg $ha^{-1}$ of Fluff. The concentration of extractable P in soil often limits plant production in agricultural scenarios, which results in the need to add P fertilizer to improve soil fertility (Potash and Phosphate Inst., 2003).

At the Borrow Pit, the soil was extremely degraded, resulting in almost no vegetation at the site at the start of the study and the initial soil fertility level being extremely low. The application of Fluff resulted in a significant increase in the extractable soil nutrients B, Ca, Co, Cu, Fe, K, Mg, Mn, P, and Zn (Table 8). This increase was likely due not only to the addition of these nutrients with the Fluff, but also due to the improvement in the soil pH level that was observed with increasing levels of Fluff application. As soil pH level increases toward neutral, the availability of most plant nutrients improves (Potash and Phosphate Inst., 2003). The addition of Fluff increased the soil extractable levels of plant macro- and micro-nutrients to levels that would allow adequate plant growth.

Soil extracts were also analyzed for concentration of the heavy metals Cd, Cr, Ni, and Pb (Table 9), which have USEPA limits for biosolids application (U.S. Government 40 C.F.R. Part 503, 1999). The concentration of Cd was increased with increasing Fluff application and Pb increased as well, but only at the highest application rate. The concentration of Cr, Ni, and Pb were also increased, but only at the highest application rate. None of the heavy metal concentrations found in the soil would be of concern in terms of the maximum cumulative loading limits as regulated for biosolids (U.S. Government 40 C.F.R. Part 503, 1999).

| Fluff rate | P | K | Ca | Mg | Mn | Fe | Zn | B | Cu | Co | Na |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mg ha$^{-1}$ | ---------------------------------------------- (mg kg$^{-1}$) ------------------------------------------------ | | | | | | | | | | |
| **Dove Field** | | | | | | | | | | | |
| 0 | 29.7 | 53.5 | 225 | 59.6 | 21.6 | 11.6 | 1.56 | 0.05 | 0.32 | 0.08 | 6.3 |
| 18 | 58.3 | 57.4 | 572 | 79.0 | 28.1 | 14.0 | 6.80 | 0.27 | 0.54 | 0.13 | 13.0 |
| 64 | 64.2 | 53.0 | 745 | 46.9 | 25.8 | 15.3 | 8.52 | 0.11 | 0.72 | 0.14 | 9.1 |
| 72 | 66.0 | 66.6 | 663 | 44.8 | 33.0 | 14.6 | 9.72 | 0.16 | 1.53 | 0.14 | 9.3 |
| 143 | 145 | 86.5 | 1835 | 79.2 | 33.3 | 16.3 | 25.4 | 0.54 | 1.67 | 0.17 | 19.4 |
| **Borrow Pit** | | | | | | | | | | | |
| 0 | 2.02 | 9.1 | 25 | 2.5 | 1.0 | 3.9 | 0.9 | 0.01 | 0.14 | 0.01 | 8.1 |
| 18 | 12.0 | 11.8 | 194 | 7.1 | 1.5 | 5.6 | 2.8 | 0.08 | 0.31 | 0.02 | 12.1 |
| 64 | 5.5 | 19.0 | 101 | 7.6 | 1.7 | 5.6 | 1.7 | 0.05 | 0.59 | 0.02 | 9.7 |
| 72 | 65.7 | 24.6 | 835 | 18.8 | 6.0 | 12.4 | 17.0 | 0.23 | 2.06 | 0.05 | 15.2 |
| 143 | 102 | 36.8 | 1511 | 41.0 | 8.6 | 23.3 | 19.7 | 0.71 | 2.42 | 0.10 | 93.9 |

Table 8. Soil extractable plant nutrient concentrations in the 0-5 cm soil depth for the Dove field and Borrow Pit study sites.

The application of the Fluff had a large impact on the soil pH, especially in the soil sampled after the first growing season. The Fluff would not be a liming material (McLean, 1982), but because of the near neutral pH and large Ca content of the Fluff material, the application of Fluff raised the soil pH. In the first year of the study, soil pH had a linear response to increasing Fluff application at both study sites. This increase in soil pH could be critical to the establishment of native grasses. Soil pH at or below the 5.3 level would be very detrimental to plant growth, resulting in nutrient deficiencies and potential Al toxicity (Potash and Phosphate Inst., 2003). The level of soil pH observed in the control plots would partially explain the complete failure of plant growth that was observed in the Borrow Pit site.

| Fluff rate | Ba | Cd | Cr | Ni | Pb |
|---|---|---|---|---|---|
| Mg ha$^{-1}$ | --------------------------- (mg kg$^{-1}$) --------------------------- | | | | |
| **Dove Field** | | | | | |
| 0 | 0.63 | 0.05 | 0.03 | 0.08 | 0.00 |
| 18 | 0.47 | 0.12 | 0.11 | 0.16 | 0.27 |
| 64 | 0.45 | 0.08 | 0.11 | 0.45 | 0.03 |
| 72 | 0.45 | 0.10 | 0.11 | 0.22 | 0.02 |
| 143 | 0.52 | 0.21 | 0.28 | 0.50 | 0.80 |
| **Borrow Pit** | | | | | |
| 0 | 0.47 | 0.01 | 0.01 | 0.02 | 0.15 |
| 18 | 0.54 | 0.01 | 0.04 | 0.10 | 0.31 |
| 64 | 0.75 | 0.01 | 0.02 | 0.05 | 0.21 |
| 72 | 1.04 | 0.07 | 0.14 | 0.31 | 0.87 |
| 143 | 1.97 | 0.13 | 0.35 | 0.77 | 2.26 |

Table 9. Soil extractable heavy metal concentrations in the 0-5 cm soil depth for the Dove Field and Borrow Pit study sites.

Soil C and N concentration was measured at both study sites. Soil C and N concentration is one of the most important factors for assessing soil quality (Wienhold et al., 2004) that impacts soil physical, chemical, and biological functions of the soil. The buildup of soil C can be essential to the long term health of the soil system.

At the Dove Field, in plots where no Fluff was applied, soil C concentration was approximately 13 g kg $^{-1}$ in the surface 0-5 cm depth and declined with increasing soil depth, down to 3.3 g kg$^{-1}$ at the 30-60 cm soil depth layer. Soil N concentration was found to be 0.6 g kg$^{-1}$ in the soil surface (0-5 cm) and fell to 0.2 g kg$^{-1}$ at the 30-60 cm soil depth layer. These levels of soil C and N are in the range expected for degraded sandy loam soils in the region. The application of Fluff had a large impact on the soil concentration of C in the soil surface (0-5 cm), increasing with increasing Fluff application up to approximately 39 g kg $^{-1}$ (Fig. 3). Likewise, a significant linear regression was observed for soil N, increasing with increasing Fluff application rate (Fig. 3). No significant impact from the application of Fluff was observed for soil concentration of C and N below the 0-5 cm depth at this location.

In the highly degraded Borrow Pit site, the soil concentrations of C and N were extremely low where no Fluff had been applied, with a C concentration of 2.2 g kg$^{-1}$ and N concentration of 0.1 g kg$^{-1}$. Interestingly, little difference was observed throughout the entire soil profile for C and N concentration, as reflected by the extremely low concentrations and the lack of any plant growth. However, the application of Fluff resulted in a significant influence on soil C in the surface 0-5 cm depth increment, with an increase to approximately 20.2 g kg$^{-1}$ for the 143 Mg ha$^{-1}$ Fluff application rate (Fig. 4). Likewise, the soil N level was increased with increasing Fluff application, to approximately 1.0 g N kg$^{-1}$ with the 143 Mg ha$^{-1}$ application rate. This level of increase in soil C and N at this depth demonstrated an improvement in soil condition and is in the range that would be considered excellent for a sandy loam soil in this region.

Unlike the Dove Field soil, significant linear regression was observed for increasing soil C and N with increasing Fluff application below the 0-5 cm depth (Fig. 4). While small compared to the impact that was observed in the 0-5 cm depth, a distinct increase in both C and N concentration could be observed with the increasing application of Fluff at the 5-10, 10-20, and 20-30 cm depth increments. This increase could be partially caused by the movement of soluble C and N compounds deeper into the soil profile. However, this increase was most likely the result of increased plant rooting with the establishment of the native grasses. The increased grass biomass observed with increased Fluff application rate would have been accompanied by increased root biomass below the soil surface resulting in increased organic matter input into the soil. This improvement in soil C and N not only at the soil surface where Fluff was incorporated, but deeper into the soil profile would be invaluable to improving the soil/plant environment on a highly disturbed soil.

The results of this study indicated that the application of a non-composted organic amendment to highly acidic, degraded soils would improve soil conditions and provide a healthier soil environment for plant establishment. The improved conditions were most prominent on the more highly degraded soil, indicating that the more degraded the soil the higher the potential benefit from the addition of organic amendments (even non-composted organic amendments).

### 4.5 Dust control

The organic byproduct of the WastAway Garbage Recycling System has proven effective as a soil amendment to reestablish native grasses following disturbance on installation training

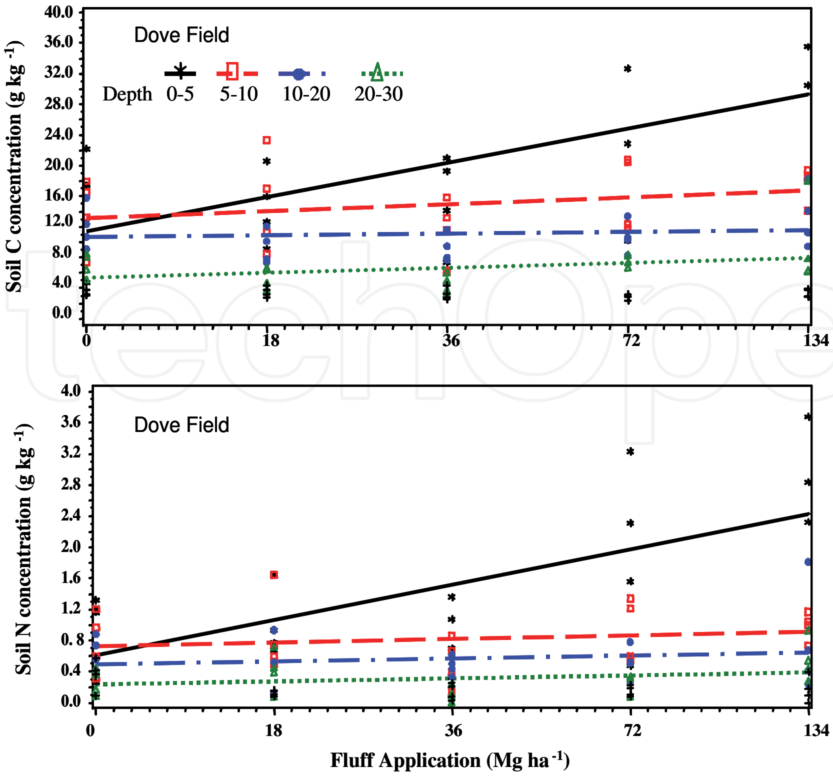

Fig. 3. Regression relationships of Fluff application rate to soil C and N concentration measured at 0-5 5-10, 10-20, and 20-30 cm soil depth at the Field study site in 2004.

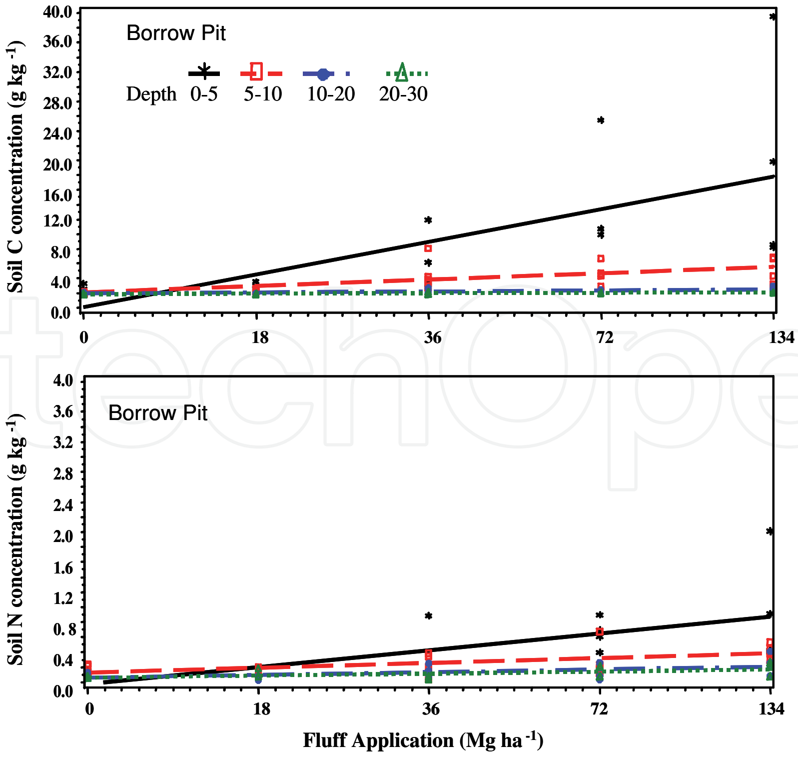

Fig. 4. Regression relationships of Fluff application rate to soil C and N concentration measured at 0-5 5-10, 10-20, and 20-30 cm soil depth at the Borrow Pit study site in 2004.

lands. Because this material is derived from the organic component of household waste, a major portion of which is cellulose, it has many peculiar properties offering potential utilization in many different scenarios, including dust suppression.

Cellulose is the most abundant carbohydrate on Earth and one of the most intensively studied organic compounds, due to its universal importance in fiber and polymer production, paper products, and numerous other industrial applications. Lignosulfonate, a paper processing byproduct, has been extensively used by Departments of Transportation in the southwestern United States and the forestry industry in the western and southeastern United States for dust control on unsurfaced county and logging roads (Gebhart and Hale, 1996). Because of the high lignin and cellulose content of Fluff, it shares similar dust control properties with commercially produced lignosulfonates. Additionally, the textural characteristics and pore space of Fluff make it an ideal candidate for use as a dust control agent alone and in combination with other dust control compounds such as vegetable oil and calcium chloride which have been used in this capacity for decades around the world (Gebhart et al., 1999).

In June of 2006, a series of field tests were conducted near McMinnville, TN, to evaluate the performance of Fluff, alone and in combination with vegetable (soybean) oil and calcium chloride. Three unsurfaced test roads were selected and divided into three segments, each of which randomly received one of the following treatments: Untreated control; Fluff alone at a rate of 35.8 Mg/ha; Fluff plus vegetable oil (100 ml/kg Fluff); and Fluff plus 38% Calcium chloride flake (10g/kg Fluff). Following treatment application, each road segment was subjected to routine local traffic for a period of 100 days to evaluate dust control efficiency through time.

At about 50 day intervals, each road segment was subjected to controlled traffic using a vehicle equipped with a mobile dust plume monitor to determine an emission index for segments of a given test road. The method chosen to determine the emission index was mobile monitoring of the PM-10 concentration in a representative part of the dust plume generated by a test vehicle on the unpaved road. A DustTRAK model 8520 was used for this purpose, with one second concentration measurements. The inlet to the DustTRAK sampling line was secured along the side of the test vehicle, thereby sampling the dust plume from the right front tire. The inlet was placed midway between the front and rear tires of the test vehicle, thereby avoiding potentially large fluctuations in the plume concentration due to the wake of the vehicle.

Emissions testing began from a stationary position at the beginning of each test segment and accelerated to 35 kph for travel and sampling through each segment. Each test provided nine DustTRAK data runs per test road. Time markers were determined for the DustTRAK output so that the reference points on the treated road segments could be correlated with the DustTRAK measurement datalog.

Table 10 shows average PM-10 concentrations for each of the dust control treatments on two dates for the three test roads. For each test road, the Fluff plus vegetable oil treatment was found to be the most effective dust control treatment, followed by Fluff plus Calcium Chloride, Fluff alone, and lastly, the untreated control. During the September 2006 testing, emission rates were substantially reduced for all test roads because of recent rains and high moisture content of the road surfaces. Nevertheless, the treated segments still showed moderate to high levels of control efficiency when compared to untreated segments, indicating that Fluff, whether alone or in combination with other dust control compounds, has the potential for low-cost, long-lasting dust control on moderately traveled unpaved roads. Given its proven potential as a soil amendment, this additional use of Fluff demonstrates yet another beneficial reuse of this municipal solid waste processing byproduct.

| Road | Sample Date | PM-10 Concentration (mg/m3) | | | |
|---|---|---|---|---|---|
| | | Fluff/Oil | Fluff/CaCl2 | Fluff | Untreated |
| 1 | 7/18/06 | 0.85 | 12.26 | 14.36 | 107.19 |
| | 9/20/06 | 0.07 | 0.07 | 0.15 | 0.83 |
| 2 | 7/18/06 | 0.61 | 3.73 | 5.73 | 56.91 |
| | 9/20/06 | 0.29 | 0.63 | 0.81 | 5.71 |
| 3 | 7/18/06 | 0.50 | 3.49 | 6.66 | 16.84 |
| | 9/20/06 | 0.31 | 1.01 | 1.22 | 2.44 |

Table 10. Average PM-10 concentration for each dust control treatment measured on two sampling dates for unpaved test roads near McMinnville, TN.

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