EVALUATION OF A MECHANICAL SYSTEM FOR RECONSTRUCTING SOIL WITHOUT TRAFFIC COMPACTION[1]

V.S. Bodapati, and L.G. Wells[2]

Abstract: Croplands in the mid-western United States subjected to surface mining pose a difficult problem for reclamation. The most perplexing problem associated with reclamation is excessive soil compaction due to the usage of heavy earthmoving equipment. Such compaction has been shown to affect the productivity of the crops grown later. This article describes design modifications to and a dynamic mechanical control system for a prototype mechanism mounted on the front of a conventional bulldozer that reconstructs soil with minimal compaction.

The mechanical system consists of a powered helical auger, approximately 1 m in diameter, mounted on a conventional bulldozer. Soil placed by scrapers or trucks in windrows or shallow strips on graded overburden is displaced laterally to form an uncompacted rooting zone approximately 1.2 m deep. Soil can be deposited in one layer or the B- and A-horizons can be deposited separately.
Modifications of the system and development of a dynamic control system to improve capacity and assure a level soil surface are described.

Excavation of a 1 ha field at the University of Kentucky Coldstream Research Farm to test the performance and efficacy of the system is described. Replicated strips (6.1 m x 120 m) are being reconstructed in triplicate using the following treatments: A- and B- horizon mixed, A- and B-horizon separated, A- and B-horizon mixed with 50 Mg/ha of compost added, and A- and B-horizon separated with 25 Mg/ha added to each horizon during deposition. Soil reconstruction capacity will be reported for each treatment, as well as soil bulk density and soil cone index six months after reconstruction.

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Introduction

Extraction of ores and minerals by surface mining has been employed for many years and reclamation of these lands has often resulted in a detrimental impact on the topmost layers of the soil. Federal and state regulations require that land should be returned to pre-mine productivity or reclaimed as per specific standards following mining. Existence of soil compaction due to the usage of heavy earthmoving equipment can prevent restoration of prime farmland to pre-mining productivity. As urban expansion removes cropland from production, restoring cropland for agriculture is equally important to society, as is the mining of fossil fuels like coal. Thus, a need for better soil reconstruction mechanisms that induce minimal compaction is of high importance. Therefore, the objective of this paper is to describe the design and principles of operation of one such prototype for reconstructing soils for agricultural lands without inducing surface traffic following surface mining.

Literature Review

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 (Public Law 95-87) is the primary federal law that regulates the environmental effects of coal mining in the United States. SMCRA grew out of concern about environmental effects of strip mining. Many controls were applied to the coal industry with regard to permitting and performance standards for surface coal mining and reclamation of prime farmland. The A and B horizons must be segregated and stored separately upon removal. These horizons must be replaced during reclamation to develop a uniform depth of 1.22 m of rooting zone with 0.3 m of topsoil over 0.91 m of subsoil. Overburden material must also be graded to approximate original contour and the post-mined landscape must blend into the surrounding undisturbed terrain (SMCRA, 1977).

State regulations must comply with essential standards of SMCRA, but can modify federal regulations to meet local conditions. Production capabilities are usually determined using randomly selected plots within a mined area. The completion of a three phase monitoring process allows the mining companies to recover the initial surety bonds deposited. Typically, the soil replacement process involves transporting and placing soil via trucks or scraper pans and then using bulldozers for final grading of the soil. Adverse compaction is often created due to the usage of such heavy equipment. Harper (1979) estimated that 48.5 million acres of prime farmland in the United States was subject to surface mining of underlying coal, whereas Vories (1997) estimated that only 10% of such lands had been mined.

Controlling the traffic patterns can reduce the compaction but final grading operations performed even with smaller dozers result in root-limiting soil bulk densities. Jansen et al. (1985) and Dunker et al. (1991a) reported the effect of physical properties of replaced soil on crop performance. Earthmoving equipment applies large pressure and the physical state of the reclaimed soil is a direct result of the method and equipment used (Dollhopf and Postle, 1988).

Two major plant growth factors affected by soil compaction are seedling emergence and root development (Chancellor, 1977). Nielson and Miller (1980) compared corn yields on strip-mined and natural soils. They reported a 4 to 90% reduction in yields on replaced mine soils. Such a reduction in soil productivity, compared to pre-mining conditions, is important to coal mining companies as they might be required to forfeit their surety bonds. Deep tillage improved yield on some reconstructed land, however, other research has shown that it has had minimal benefit for short period of usage (Gaultney et al, 1982).

Compaction of soil is an important parameter studied by researchers for almost half a century now and plays an important role with regard to plant growth. Underwood et al. (1981) have documented changes in soil properties due to coalmine reclamation that influence crop production. The primary changes have been due to lowered water holding capacity and lowered infiltration.

Dunker et al. (1991b) proposed an innovative material handling system by using dump trucks to back-fill a mined area. The trucks would be loaded by filling the front with topsoil (A-horizon) and the rear with subsoil (B-horizon). The mixture would then be back-dumped onto a graded spoil base, allowing most of the topsoil to remain at the top of the soil pile. A German method called "Wheel-Conveyor-Spreader system" was reported by Dunker et al. (19992b) to result in increased yield compared to scrapers. Large bucket wheel excavators where used to remove and mix the A- and B-horizons. A rotating bucket dug soil from the embankment and a belt conveyor transported the mixed soil horizons to a spreader. This method proved to be too expensive for usage in the mid-western United States.

Fulton et al. (2002) described a mechanical device for replacing soil materials (A and B horizons) without subjecting soil to traffic compaction (see Fig. 1). Excavated soil is deposited on a graded base using scrapers or large dump trucks. A conventional bulldozer equipped with a helical auger displaces the deposited soil laterally into an uncompacted berm. The depth of the berm is controlled by the height of the auger above the base. Preliminary tests verified that soil could be reconstructed in this manner; however, the time rate of soil reconstruction was less than anticipated in the design of the system (Fulton and Wells, 2004).

The primary objective of this study was to modify the system described by Fulton et al. (2002) to increase soil reconstruction capacity and to reduce or eliminate uneven surfaces of reconstructed soil profiles. The secondary objective was to determine the effects of a) soil horizon segregation and, b) addition of organic matter upon productivity of reconstructed soil.

Materials and Methods

The mechanical system for replacing soil materials described by Fulton et al. (2002) (Fig. 1) was modified and evaluated in this study. The system was modified in several ways to improve the performance. The soil regenerator, as it is called, was mounted on the front of a conventional Caterpillar D7 bulldozer and employed a 91 cm diameter auger with a blade. The auger's elevation was adjustable relative to the blade and the spiral action of the auger agitated the soil in front to deposit it in a berm adjacent to the windrow. An auxiliary engine was used to power the auger and this was done so as not to diminish the power of the bulldozer. Fulton et al. used a semi-universal blade with a straightened right end and two hydraulic cylinders were used to adjust the vertical position of the auger. A wear plate was added between the support structure and the blade to transfer the lateral force generated by the auger. The framework was steel and the center core of the auger consisted of seamless and cold-drawn mechanical tubing.

The blade and auger assembly was remounted at an angle of 6^0 from perpendicular to the direction of travel to improve lateral displacement of soil with forward movement of the bulldozer blade. The powered auger was placed in front of the blade and its elevation was adjustable as before. An extension was added to the right end of the blade. The blade extension can be extended or retracted by the operation of a double acting hydraulic cylinder. The position of the adjustable blade extension is determined by an automatic control system. Figure 2 shows a sketch of the modified soil regenerator.

Figure 1. Mechanical system for reconstructing soil mounted on a conventional bulldozer, before improvements.

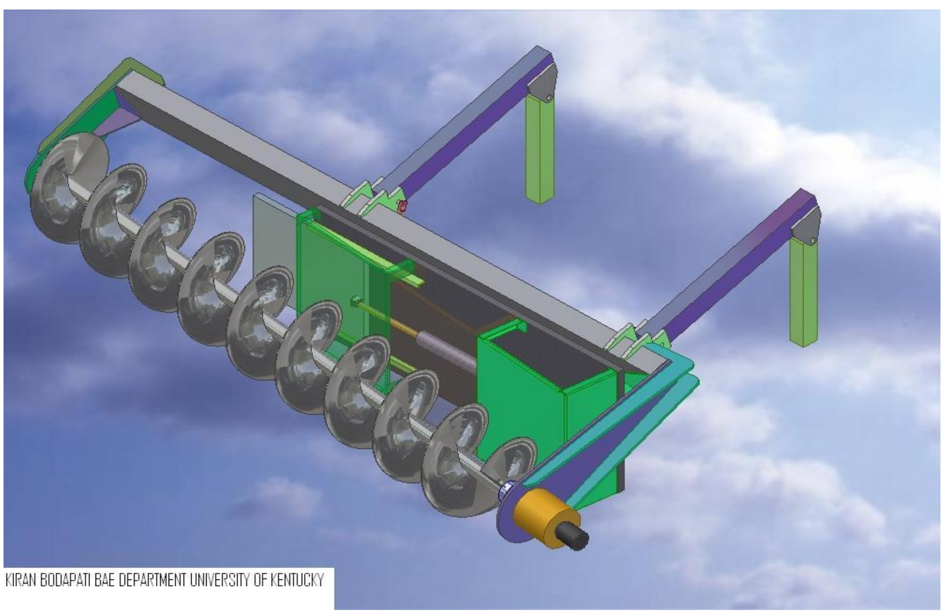

Figure 2. Soil regenerator assembly showing blade and auger oriented 6^0 relative to perpendicular to direction of travel and mechanically controlled blade extension.

<u>Description of the Control System Mechanism</u>

The dynamic blade width control system utilizes electro-mechanical sensors mounted at the end of the auger (see Fig. 3). Wheel assemblies are mounted on the end of steel rods 3.18 cm (1 ¼") in diameter. Linear position transducers are mounted on the front and rear units, consisting of Unimeasure Corporation type JX-EP digital encoders measuring approximately 63 cm (25”) of vertical displacement.

Figure 4 illustrates the functioning of the dynamic control system. When excess soil at the end of the auger causes sensor 1 to rise, the blade extension moves inward to increase fill zone volume (see Fig. 4). When sensor 2 drops into a depression beneath the auger, the blade extension moves outward to decrease the fill zone volume (see Fig. 4).

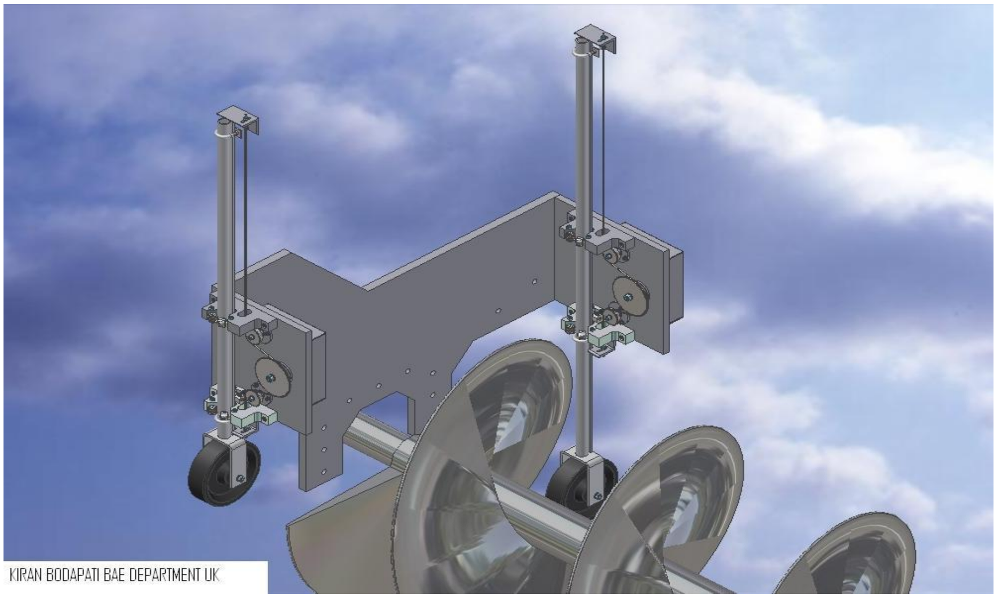

Figure 3. Dynamic control system at the right end of the auger.

A PCI-Quad 04 data acquisition module, manufactured by Measurement Computing Corporation is used to read digital input from the sensors. The output from the encoders is in digital quadrature form and gives an indication of the exact extension/retraction of the wire rope and the direction in which the pull is occurring. PCI-Quad 04 has two 24-bit dual axis LS 7266 quadrature counters.

The input channels on the board have been configured to differential ended mode and InstaCal software developed by Measurement Computing was used to install the board onto the computer. A third linear position sensor, manufactured by Celesco Corporation, is used to measure the blade extension position. This transducer measures 63.5 cm (25”) of total extension and gives an output in the form of an analog signal. A Measurement Computing PMD-1208 LS is used to read the input from this board, as the PCI Quad-04 does not have capability to read analog input. The PMD-1208LS has digital output capability as well and is used to control the operation of a solid-state relay that opens or closes a solenoid operated directional control valve.

Measurement Computing supplies a universal Visual Basic library with built-in functions, which can be programmed as per user requirements. InstaCal is used to install the PMD-1208LS as well and a unique board number is assigned for use by the program. The program to control the entire system is written in Microsoft Visual Basic 6.0 and the two data acquisition modules are programmed to read the input from the three sensors and thereby operate the relay. LS7266 counters on the PCI-quad04 board are configured and loaded with an initial value and timers are enabled to count the number of pulses changing in the input. Registers are configured to read dual-axis counters. Transducers A and B sense the height of the mounds and the depth of depressions, respectively (see Fig. 4). Both A and B are calibrated to convert the counts read to a value in inches. The direction of the extension is found by the way the status bits change. The universal library has a set of functions that configure the way these status bits are set-up and the formatted output is finally sent out to the user screen.

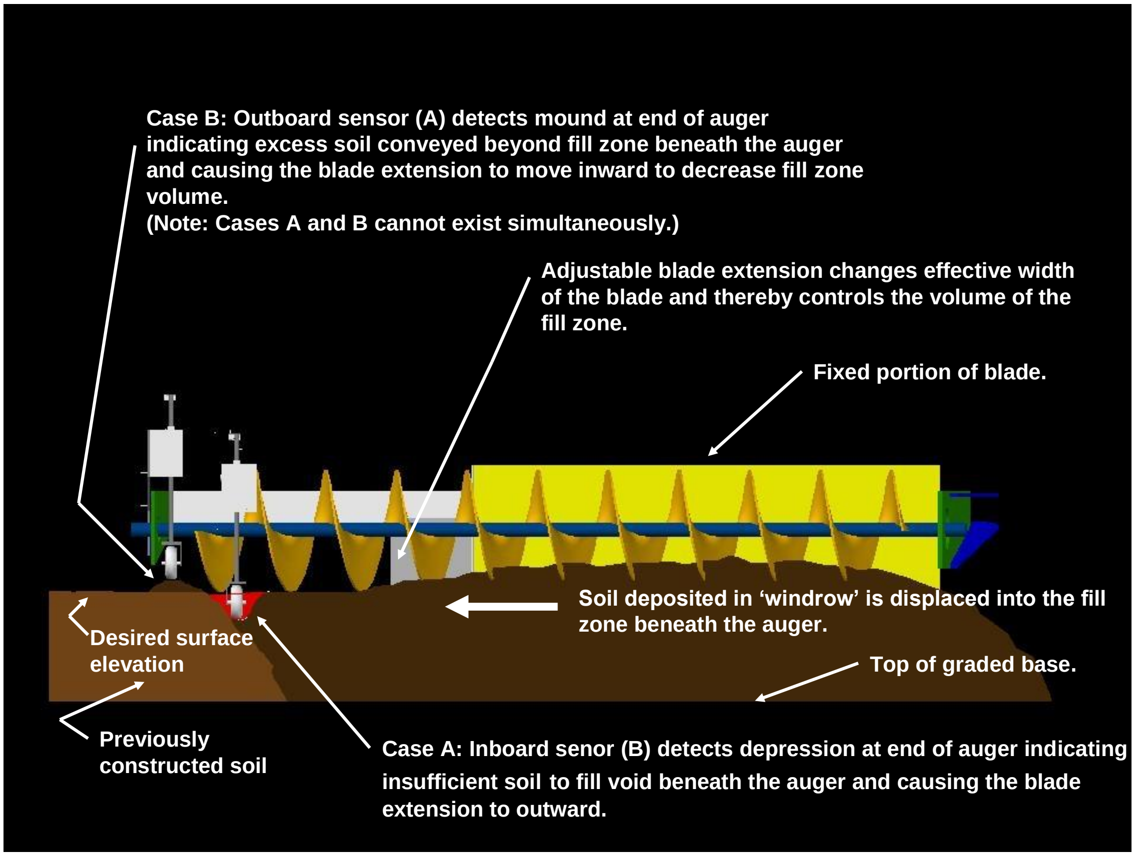

Figure 4. Front view of blade/auger assembly illustrating automatic control system for maintaining level surface of reconstructed soil.

The third sensor C is programmed differently than A and B. C had 4 outputs that are fed into the PMD-1208LS. Sampling rate is set to 1000 samples per second and a gain of 10 volts is set for the system. Registers have to be configured initially to set aside memory to hold the data points. All the digital ports of the PMD-1208LS are configured for digital output so as to have relay operations performed sequentially. The sensor C is calibrated using standard length from a ruler as the standard. The characteristic equation generated by Excel is encoded in Visual Basic to compute the appropriate position of the blade extension. A text file is created in the user specified directory and all the data being read by the three sensors is logged in this file. This text file can later be opened in Excel to get an indication of soil profile excess/deficit and how effective the blade operation was in response to the inputs sensed.

The two soil sensors A and B send the signals to the data acquisition module determining soil profile status. The program has been written in a way so as to cause equivalent action only when the input from A is for that of a mound. Similarly, the sensor B that is present at the rear end of the auger is programmed in a way so as to cause equivalent action only when it reads the input from a depression. The threshold for retraction or extension of the blade extension cylinder is a movement of 5.08 cm (2”) by sensors A or B, respectively.

The solenoid operated directional control valve used here was manufactured by Parker Hydraulics and has 24 V of DC excitation voltage. This valve is operated through a solid-state relay that controls the direction in which the hydraulic fluid is being pumped. As an example, 15.24 cm (6”) of mound travel would mean that the blade extension moves inward 15.24 cm (6”) to increase soil fill volume. The relay is triggered accordingly to cause the blade to move in. The third sensor C functions in the following manner. It sends in a signal back to the central control unit of an estimate of how much the blade actually moved. On comparison of this value with the value actually intended, the program can decide the point of stoppage for the extension. The feedback sensor plays an important role in deciding the point when the valve has to be closed. Again, if the transducer B senses 10.16 cm (4”) of depression, in this case the blade has to be moved outward 10.16 cm (4”) to avoid decrease fill volume.

The block diagram in Fig. 5 below describes an outline of how the system is configured. The laptop computer acts as the central module controlling operations.

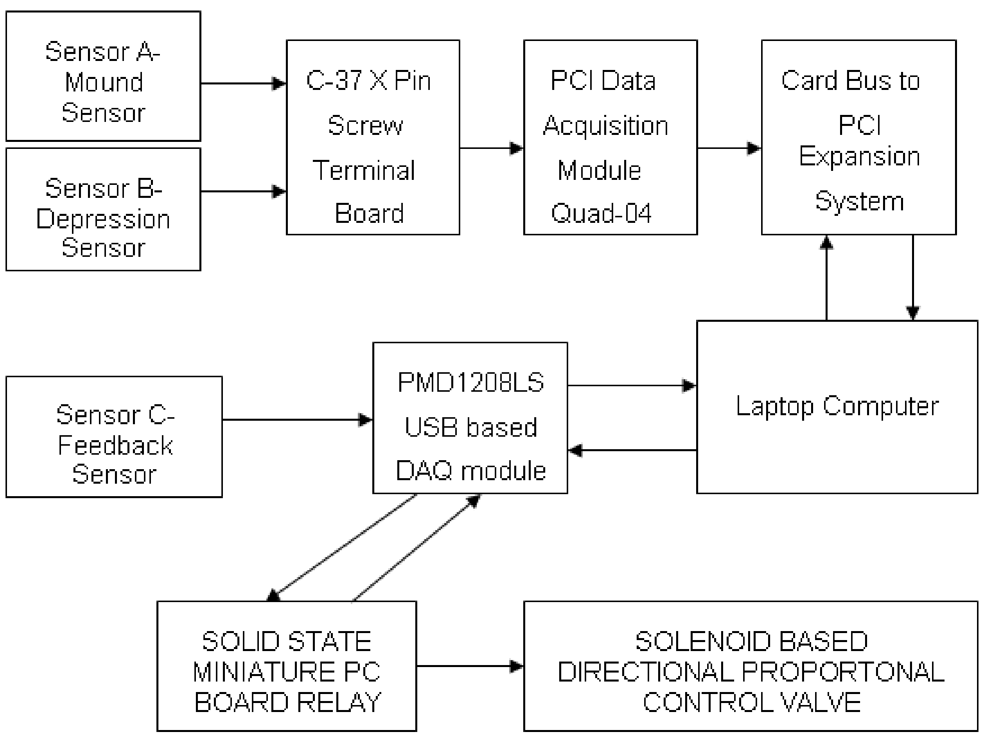

Figure 5. Block diagram of electronic control system.

As shown below in Fig. 6, the linear position transducers A and B are connected to the PCI data acquisition module through 6 wires. The details regarding the set-up are: Black-Common ground, Red-Input voltage, White and Green-Channels X and Y, Orange and Blue-Channels X0 and Y0. The last two are the compliments of the inputs read from channels X and Y. Since A and B are of the same type, similar kind of connections exist for the other transducer as well. Sensor C has a much simpler set-up and has 4 connections to be made between the transducer and the PMD-1208LS unit. These are: Black-Common ground, Brown-Input voltage, Blue-Universal ground, White-Channel to be read. The screw terminal board C-37 is an extended version of the input to the PCI-Quad04 board. It provides the user a spread out version of the pins so as to easily navigate between the connections. A data bus cable of 37 pins is used to connect the screw terminal board with PCI-quad04.

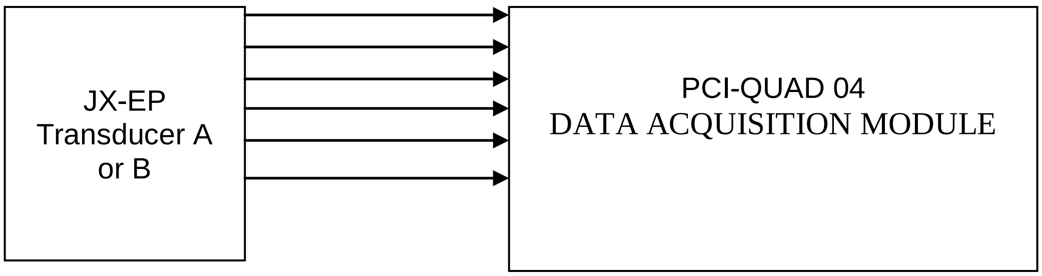

Figure 6. Layout of the electrical connections of Sensor A or B.

A Visual Basic front-end interface is the primary feature that enables the user to operate the control system as per the requirement (see Fig. 7).

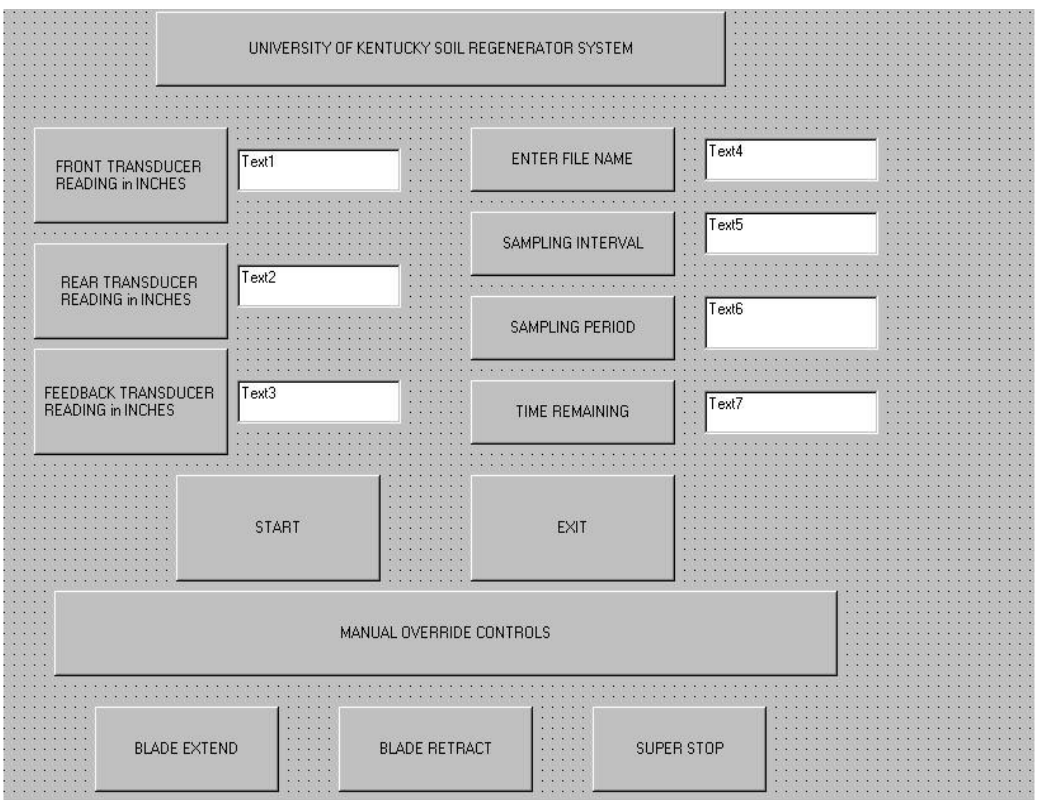

Figure 7. Visual Basic front-end interface for the dynamic control system.

The readings of the transducers A, B and C are displayed by the interface. The user initiates the program by entering the filename where the data has to be logged. The user can enter the sampling period and the sampling interval if a specific period is required, but if these values are not entered, the program assumes default values of 1000 samples per second for a period of one hour. The exit button stops the data logging operation and the manual override controls are handy in terms of controlling the blade to perform specific features as per the user needs. Many times in the field, situations could be anticipated where either greater or lesser soil fill volume is required than that determined by the control system. Blade extension cylinder retraction and extension are controlled by separate sub-routines in the program that enable the user to perform these operations and thus over-ride the automatic control system. Super stop is the ultimate stop button that would supersede all other operations when used and would bring all the operations to a halt. It has the highest priority in its set-up and can be used as per the requirement.

The text file logs the instant readings of the front, rear and feedback transducers. These readings can be used to plot depth of depressions and height of mounds as a function of the blade movements. Such an analysis would give a detailed insight on how the system responded actually to the soil profile.

Field Experiments

Excavation of approximately 1 ha of land located at the University of Kentucky Coldstream Research Farm was initiated in August 2006 using a scraper. The area dimensions are approximately 85 m by 120 m. The mean depths of the existing A- and B-horizons at the site were measured at multiple locations, resulting in mean values of 25 cm and 90 cm, respectively. A-horizon soil was removed from approximately half the site and stored nearby using a scraper pan. B-horizon subsoil was removed from these strips to a maximum depth of 90 cm and stored in a separate location. A- and B-horizon soils will be removed from the remaining half of the site so as to achieve thorough mixing of A- and B-horizon soils.

The mechanical system as modified in fig. 2 was tested briefly in September 2006 (see Fig. 8). Although the blade was remounted on the bulldozer at 6^0 from perpendicular, soil was not efficiently moved from the windrows deposited by the scraper into the reconstructed berms. We theorized that this was mainly due to pushing directly into the windrow, owing to the vertical orientation of the blade. Thus, we modified the blade by adding a section extending forward at the base to lift soil onto the blade as the dozer pushes forward. After the modification was completed we experienced record rainfall for the months of September and October and were unable to complete testing. We plan to begin testing as soon as soil is dry enough to operate at the site in 2007.

Soil will be replaced as soon as possible in 1.2 m wide parallel berms using the mechanical soil replacement system as follows. Four replacement treatments will be randomly assigned in triplicate to the site in 6.1 m wide strips (see Fig. 9). In treatment 1, B-horizon soil will be deposited at the base of the excavated site in layers (windrows) approximately 3 m wide by 0.5 deep by the scraper. The blade of the modified dozer will then engage each layer, displacing soil laterally and vertically into the auger. The dynamic control system along with the modified blade should be able to displace the soil laterally without inducing any compaction. The spiraling action of the auger and the control system will help in creating landscape in such a way that it blends in with the surroundings. Displaced B-horizon material of treatment-1 will accumulate in a berm 1.35 times the average depth of the original B-horizon (to account for soil 'swell') at the site, determined by the height of the bottom of the auger extended to the right of the blade. Next, the scraper will deposit a windrow of A-horizon soil (approximately 3.5 m wide and four times the depth of the original A-horizon) adjacent to the replaced B-horizon berm. The mechanical system then will displace and deposit the A-horizon soil atop the 1.2 m wide B-horizon berm, resulting in A-horizon soil atop B-horizon soil to a maximum depth of 1.2 m. This process will be repeated 5 times for each replication resulting in three 6.1 m wide strips randomly located on the site. Holes (approximately 121 cm x 71 cm x 121 cm) were dug at three different locations on the site to determine soil volumetric expansion (swelling) to be approximately 35%. This will determine the elevation of the auger as each layer of soil is deposited. The soil that has been dug out is placed back into the pit and the left over soil is measured to find out the amount of swell.

Figure 8. Mechanical system tested in September 2006.

Treatment 2 will be achieved by placing mixed A- and B-horizon soils in windrows and constructing similar berms to a maximum depth of 1.2 m. Replications of this treatment will consist of three 6.1 m wide strips randomly positioned on the site. Treatment 3 will be achieved by the same methods described for Treatment 1, except that 25 Mg/ha of composted beef cattle manure/bedding will be placed atop the windrows of B-horizon soil placed by the scraper. The compost will then be mixed with B-horizon soil by the mechanical replacement system as the berms are constructed. An additional 25 Mg/ha of compost will be placed atop windrows of A-horizon soil and then deposited atop B-horizon soil as described above.

Finally, Treatment 4 will be achieved by placing 50 Mg/ha of compost atop windrows of mixed A- and B-horizon soils before being displaced by the mechanical system. This operation will result in the organic material being mixed into the upper portion of the replaced berms. The replaced plots will be mulched and seeded in hairy vetch as construction proceeds without allowing traffic on the plots. The plots will be planted in corn, beginning in Spring 2008 and continuing through 2010. Standard no-till production methods employed by the UK farm manager will be used throughout the study.

A and B horizons with compost (rep 3)
One horizon, no compost (rep 3)
One horizon with compost (rep 3)
A and B horizons, no compost (rep 2)
A and B horizons with compost (rep 2)
A and B horizons with compost (rep 1)
One horizon with compost (rep 1)
One horizon, no compost (rep 1)
A and B horizons, no compost (rep 3)
A and B horizons, no compost (rep 1)
One horizon with compost (rep 2)
One horizon, no compost (rep 2)

Figure 9. Schematic of randomized arrangement of reconstructed soil treatment replications (each strip is approximately 6.1 m by 120 m).

Expected Results

Fulton and Wells (2004) reported that the mechanical system reconstructed soil at 600 m^3/hr. Proposed modifications should increase the reconstruction rate to 1,500 m^3/hr, which would support five 15 m^3 scrapers delivering loads at 3-minute intervals or two 75 m^3 trucks unloading at 10-minute intervals. If such capacity can be attained, the system should allow soil reconstruction without compaction that does not compromise production.

We expect mechanical soil replacement to result in soil bulk density and a soil cone index level equivalent to or less than those existing before the site is disturbed. We also expect that corn yield for the mechanically replaced plots to be equivalent to or greater than that recorded for the site prior to disturbance.

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