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Fragipan Horizon Changes Using Annual Ryegrass and Other Admendments

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Abstract

A greenhouse experiment was conducted involving intact fragipan soil cores of 50 cm thickness after removing the topsoil horizons. The cores were maintained in moist condition throughout the experiment and received several treatments with various amendments for different periods ranging from 9 to 17 months. The amendments included annual ryegrass or Festulolium residues, powder limestone and various humate compounds alone or in combination with the grass residues. The results suggested a significant effect of ryegrass and Festulolium in reducing penetration resistance into the top 10 cm of the fragipan within 9 - 17 months, particularly when used in combination with certain humate materials such as Leonardite. Apparently, this is the result of the release of certain soluble organic compounds from the plant residues or the humate amendments that increase the solubility of Si and Al associated with the fragipan brittleness, thus decreasing the density of the compacted fragipan material.

Keywords

Fragipan, Fragipan Horizon, Fragipan Soils, Changing the Fragipan, Annual Ryegrass Changes Fragipan, Festulolium Changes Fragipan, Amendments That Change the Fragipan

1. Introduction

The fragipan is a naturally occurring restrictive soil horizon that virtually stops water movement and root growth through the soil. Fragipans occur in more than 80 million square km in the United States [1]. They are commonly located 45 - 60 cm below the soil surface. The dense nature of these layers is due to the cementation and binding of the soil particles with a silicate-rich amorphous aluminosilicate sometimes in association with iron (Fe) or manganese (Mn). These binding agents seal the pores and pack the soil particles close together [2].

Fragipans usually reduce plant available water-holding potential to about one-half of that observed in many other crop-producing soils [3] [4] [5] [6]. They commonly cause over-saturation with water above the fragipan layer during the winter and spring, which results in adverse soil conditions for the crops growing during this time [7]. However, by far the biggest production problem for corn and soybeans grown on these soils, which under normal soil conditions can extend their rooting systems below 100 cm, is the limited water-holding capacity at critical growth stages. Plant water deficits at reproductive and grain-fill periods may reduce yields by at least 20% - 25% [8] [9] [10].

Although there are many studies on the nature and characteristics of fragipans, there have been very few attempts to find methods that would accelerate fragipan degradation and remediation [7] [8] [9] [10]. Karathanasis *et al*. [11] used a slaking method and found 3 amendments in addition to annual ryegrass (ARG) that could degrade fragipan clods. Also, Matocha *et al*. [12] reported reduced bulk densities and tensile strengths in fragipan aggregate matrices in fields with ryegrass (*Lolium multiflorum*) cover crop compared to those without cover.

The approach used in this study involved an in situ reactive method utilizing undisturbed fragipan soil columns subjected to leaching with different amendments for a period of up to 17 months in the greenhouse of the University of Kentucky Research and Education Center at Princeton, Kentucky. This technique was used to corroborate our previous research findings with fragipan clod slaking experiments (Karathanasis *et al*. [11] and Matocha *et al*. [12]) utilizing undisturbed fragipan soil column sections and monitoring changes in the fragipan layer by the different amendments over the designated time. The purpose of this research was to determine the relative effectiveness and rate of change by different plants and amendments placed on an undisturbed and intact fragipan.

2. Materials

Undisturbed cores of a Zanesville silt loam fragipan soil (fine-silty, mixed, active mesic, oxyaquic fragiudalf) were collected with a hydraulic probe fitted with a 12-cm diameter transparent plastic sleeve to a depth of 100 cm, which was the lower depth of the fragipan horizon. The upper horizons lacking fragipan properties (about 50 cm) were removed exposing only the bare consolidated fragipan section to the surface. Different chemicals (sodium fluoride (NaF), powdered limestone, humates, plant tissues and combinations) were lightly mixed into the top 1 to 2.5 cm of the upper fragipan core, which was kept moist during the period of the treatments. These materials were selected because they showed positive effects in our previous lab experiments with fragipan aggregates (Karathanasis *et al*. [11], Matocha *et al*. [12]). The control cores did not receive treatments and were also kept moist for the same period. When plant materials were used as amendments, the plants were grown in separate containers in the greenhouse. The shoot foliage and roots were harvested, dried and ground for use as an additive. A 5 mm pointed penetrometer with an applied pressure of 620.5 kPa was used to measure the depth of penetration in each core at the end of the experiments.

3. Methods

The first experiment involved an application to the top of the fragipan cores a mixture of NaF and ARG tissues and lasted 18 months. The second experiment included a combination of several humate materials with powdered limestone for a duration of 9 months. The third experiment involved a combination of humate materials and ARG tissues and lasted 12 months. The fourth experiment included a combination of ARG and festulolium clippings over a period of one year. Three replicate cores were used for each treatment. The effectiveness of each treatment to reduce the strength, hardness, and structure of the fragipan was measured by the penetration depth into the fragipan core by a penetrometer, as well as, the depth of structural changes in the fragipan core. The penetrometer was pushed into the fragipan until the resistance exceeded 620.5 kPa. Three readings were made on each core and with the three replications, nine total readings were made.

The cores were then cut apart and examined for any structural changes. If the fragipan core changed in an uneven pattern by depth, the deepest depth was determined to be the depth of disintegration. The disintegration of the fragipan in the treated cores was evident as a combination of bleached soil particles and loose soil structure compared to the untreated cores that showed mainly a brown consolidated matrix. This brown consolidated matrix with mainly prismatic structure and dead-end short gray streaks was also evident below the treatment depth of the treated ores (**Figure 1**).

Figure 1. Fragipan cores untreated (left) and treated with sodium fluoride (NaF) and annual ryegrass (ARG) after one year.

Experiment 1: Effect of Ryegrass and Sodium Fluoride on Fragipan Degradation

Fragipan cores were collected and prepared as previously described. This experiment involved 4 treatments with 3 replications each. The treatments included: the control, annual ryegrass (ARG), the NaF powder and the combination of ARG and NaF.

Bounty (ARG) was grown in the greenhouse. Shoot foliage growth and roots of ARG were collected and ground separately. The applied dried shoot growth rate was 10,090 kg/ha and the dried roots at 4012 kg/ha. The application rates were similar to the dry matter mass expected in field trials. The NaF powder was applied at 112 Kg/ha. The combined ARG and NaF treatments involved the same application rates. The amendments were mixed into the top 2.5 cm of the fragipancores, while the untreated control remained undisturbed. All the cores were kept moist during the period of the experiment. Two applications of these amendments were made within a six-month period. The final measurements were taken one year after the second application. At that time, the depth of penetration by a 5 mm penetrometer at 620.5 kPa was recorded and the cores were dissected and evaluated for structural, color and chemical changes by depth. The results are listed in Table 1 and Table 2, including statistical differences among treatments determined using SAS Studio software (SAS Inc., Cary, NC).

Table 1. Effect of annual ryegrass (ARG) and sodium fluoride (NaF) on penetrometer depth (cm) and depth of structural changes into the Fragipan 18 Months after a Surface Application of the treatments. Different capital letters indicate significant difference between treatments based on the least significant difference at 95% significance level.

Treatment	Penetration depth (cm)	Depth Change (cm)
Control	3.02 C	2.54C
ARG	9.64 B	8.89B
NaF	3.26 C	5.08C
ARG + NaF	13.7 A	12.7A
CV	18.78	23.0
P	<0.01	0.01

Table 2. Effect of Annual Ryegrass (ARG) and Sodium Fluoride (NaF) on soil pH and Nutrient Content ($mg \cdot kg^{-1}$) of Soil Layers at Different Depths (1 = 5 cm, 2 = 10 cm, 3 = 15 cm) Below the Surface of Treated Fragipan cores, 18 Months after Application (Average of Three Replications).

Treatment	Depth	pH	P	K	Ca	Na
Control	1	3.39B	1.33C	160B	1422B	119C
ARG	1	6.01A	267A	1368A	2416A	499B
NaF	1	3.51B	2.00C	151B	1437B	237C
ARG + NaF	1	5.90A	220B	1331A	2543A	711A
CV		3.62	12.7	3.53	19.4	19.1
P		<0.01	<0.01	<0.01	<0.01	<0.01
Control	2	3.31B	0.67B	146B	719B	147B

Continued

ARG	2	3.45A	15.0A	661A	909A	223A
NaF	2	3.31B	1.00B	150B	814A	278A
ARG + NaF	2	3.49A	10.0A	612A	1081A	293A
CV		0.84	28.2	8.28	18.6	9.72
P		<0.01	<0.01	<0.01	0.13	<0.01
Control	3	3.24	1.33	157B	895	146
ARG	3	3.25	4.33	391A	840	163
NaF	3	3.31	1.50	145B	707	163
ARG + NaF	3	3.29	2.33	406A	857	200
CV		1.20	50.0	12.2	50.8	12.1
P		0.28	0.07	<0.01	0.96	0.06

The results of this trial indicate that both additives had a significant effect on changing the structure and the strength of the fragipan matrix. Comparing the additives individually, the ARG was much more effective. The NaF effect was small but showed a significant synergistic effect when combined with the ARG. The penetrometer resistance changes (**Table 1**) and the visual changes in soil structure (**Table 1**) occurred at similar depths and appeared to be of equal value in predicting the conversion of the fragipan to soil that would support root growth.

There was a significant accumulation of nutrients particularly in the top 5 cm of fragipan cores (**Table 2**) treated with dried ARG foliage and roots. Also, the accumulation of phosphorus (P), potassium (K), calcium (Ca) and sodium(Na) in the top 5 cm of the fragipan was much higher as was the pH, compared to the depths below where ARG was applied to the surface [12] [13]. The positive effect of ARG was evident particularly in the upper 10 cm of the fragipan in spite of a smaller magnitude in the lower 5 cm depth. Similar trends were also observed for the combined ARG + NaF treatments. These treatments suggest that the addition of ARG or ARG + NaF amendments can alter fragipan layers within a short period; 10 cm of a previously impervious and restricted fragipan soil domain changed into a water and nutrient-accessible environment that should definitely result in higher crop yields. No significant pH or nutrient increases were observed below the 5 cm fragipan depth by any of the amendments, but this can be ameliorated with a powdered limestone application (Karathanasis *et al.* [11]).

Experiment 2: Effect of Different Humate Materials and Limestone on Degradation of the Fragipan

The objective of this trial was to determine the effectiveness of some commercially available amendments to degrade the fragipan. A powdered agricultural limestone (200 mesh) was compared to two soil conditioners and humic acid. There is some evidence that some of the humate materials may have a positive effect on the soil structure [14]. The materials applied and the corresponding rates are listed in **Table 3**.

Table 3. Materials and Application Rates used in the humate and limestone treatments.

Treatment	Rate (kg/ha)
Control	No Treatment
Leonardite Humate*	560 kg/ha
Menefee Humate**	560 kg/ha
Powdered Limestone	2242 kg/ha
Humic Acid Powder	112 kg/ha

*Leonardite is an oxidized lignite used as a soil conditioner. **Menefee is a sub-bituminous material used as a soil condition.

Fragipan cores were collected and prepared as previously described. The materials were applied to the surface of the intact fragipan cores except for the control and mixed into the top 1.5 cm at the rates described above. There were three replications for each treatment, and the cores were kept moist during the trial. A second application was made four months after the first application. The reported results were collected nine months after the first application. The depth of penetration measurements was made with a 5 mm penetrometer at 620.5 kPa as in the first experiment. At the end of the experiment, the cores were also dissected and evaluated for structural and color changes.

Table 4. Effect of Different Humate Materials and Limestone on the Penetration Depth into a Fragipan and the Structural Change of Fragipan Cores as determined by visual examination 9 Months after a Surface Application of the Treatments.

Treatment	Penetration depth (cm)	Depth Change (cm)
Control	2.25C	1.86C
Leonardite Humate 560 kg/ha	5.99A	5.38B
Menefee Humate 560 kg/ha	4.33B	7.20A
Limestone 200 mesh, 2242 kg/ha	5.78A	5.08B
Humic Acid Powder 112 kg/ha	2.25C	2.54C
CV	13.7	37.8
P	<0.01	0.02

As seen in **Table 4**, both humates and powdered limestone effectively changed the soil structure of the top of the fragipan zone [11] [14]. The humic acid treatment measurements were similar to the control. The depth of the penetrometer measurements and the depth of the observed structural changes were similar for the Leonardite Humate and powdered limestone. The measured effectiveness of the Menefee Humate differed between the penetrometer and the visual structural change evaluations, but both indicated a positive response to the application. The results indicate that the two humate compounds and the finely ground limestone will be effective in degrading part of the fragipan zone even within nine months after application.

Experiment 3: Effect of Different Humate Materials and Annual Ryegrass on Degradation of the Fragipan

The objective of this experiment was to assess the effect of the two humates that showed positive effects on degrading the fragipan zone in the previous experiment in combination with ARG residue application. Humates are added to soils as soil conditioners to help improve the existing soil structure. There is some evidence that some of the humate materials may have a positive effect on the soil structure [14] [15] [16]. Annual ryegrass is proven to be able to change the fragipan from a hard impermeable layer to a productive soil structure [12]. The objective of this trial was to determine the relative effectiveness of the application of a humate in combination with ARG residues. The materials and application rates are listed in Table 5.

Table 5. Materials and Application rates used in the 3rd experiment.

Treatment	Rate kg/ha)
Control	No Treatment
Annual Ryegrass (ARG)	10,090 kg/ha top growth + 4012 kg/ha roots
Leonardite* Humate + ARG	560 kg/ha + ARG as above
Menefee** Humate	560 kg/ha

*Leonardite is a mined oxidized lignite used as a soil conditioner. **Menefee Humate is a mined sub-bituminous used as a soil conditioner.

Fragipan cores were collected and prepared as previously described. The materials described in Table 5 were applied to the surface of the intact fragipan and mixed into the top 2.5 cm at the rates described in Table 5. There were 3 replications of each treatment, and the cases were kept moist during the trial. A second application was made four months later. The reported results were taken one year after the initiation of the experiment. The depth of penetration measurements was made with a 5 mm penetrometer at 620.5 kPa. The cores were dissected and evaluated for structural and color changes. A 5 cm section of each core beginning 5 cm below the core surface and ending 10 cm below the core surface was used to measure bulk densities.

Table 6. Effect of different humate materials and annual ryegrass on the penetration depth and structural and color change of fragipan cores as determined by visual examination into a treated fragipan one year after the first surface application of the treatments.

Treatment	Penetration depth (cm)	Depth Change (cm)
Control	2.94D	2.54C
ARG 10 K kg/ha + 4 K kg/ha Roots	8.64B	9.74B
Leonardite Humate 560 kg/ha + ARG Shoots Roots (above)	10.8A	14.0A
Menefee Humate 560 kg/ha	5.50C	6.77B
CV	10.1	21.3
P	<0.01	0.01

Table 7. Effect of different humate materials and annual ryegrass on the bulk density change of fragipan cores in the 5 - 10 cm zone one year after the first surface application of the treatments.

Treatment	Bulk Density in 5 - 10 Fragipan Zone (gm/cc)
Control	1.82B
Annual Ryegrass	1.65A
Leonardite Humate + Annual Ryegrass	1.60A
Menefee Humate	1.62A
CV	3.8
P	0.02

As has been shown in the previous experiments, ARG is very effective as a component to degrade the fragipan properties. In this experiment, the application of ARG residues showed consistently high degrading effectiveness, particularly when combined with Leonardite Humate in terms of penetration depth, visual examination of depth to the unaltered fragipan, and bulk density, compared to the control (Table 6 and Table 7). The humate (Menefee) also had a degrading effect on the fragipan compared to the control as seen by the deeper penetration depth, the visual soil structural change and the lower bulk density but much lower than the ARG or the ARG+ Leonardite humate treatments.

Apparently, combining ARG residue and Leonardite humate results in a synergistic effect that generates more effective chemical reactions than ARG alone, thus, being conducive to faster degradation of the fragipan matrix.

Experiment 4: Effect of Annual Ryegrass and Festulolium Grass on Degradation of the Fragipan.

Annual ryegrass is the only plant that is proven to be able to change the fragipan from a hard impermeable layer to a functioning soil like structure [9] [12] [13]. Festulolium grass is a genetic cross between fescue and ARG. This trial was set to determine whether Festulolium also possesses similar constituents to ARG that will provide the potential to degrade the fragipan matrix.

Fragipan cores were collected and prepared as previously described. Festuloleumgrass (shoot and roots) were dried, mixed and applied to the surface 2.5 cm of the fragipan at the rates described below. There were three replications for each treatment, and the cores were kept moist during the trial. The applied rates are similar to the dry matter mass expected to be produced in field trials, amounting to 10,090 kg/ha for top growth and 4012 kg/ha for roots and a total mixture of 14,102 kg/ha). The measurements were taken seven months after application and are reported in Table 8. As was done in the previous experiments, the penetration depth was measured with a 5 mm penetrometer at 620.5 kPa and the cores were dissected and evaluated for structural and color changes.

The results of this trial indicate that the genetic traits of the ARG facilitating the degradation of the fragipan also exist in Festulolium. The penetration depth was similar for the two grasses (Table 8), but the visual examination of the dissected cores indicated a greater degradation depth by Festulolium. Overall, both of these grasses appeared to be the best options for faster and deeper degradation of the fragipan matrix.

Table 8. Effect of annual ryegrass and festulolium grass on the penetration depth and on the depth of structural change of fragipan cores as determined by visual examination into an unaltered fragipan 7 months after a surface application.

Treatment	Penetration depth (cm)	Depth Change (cm)
Control	2.68B	2.54C
ARG 10 K kg/ha Shoots + 4 K kg/ha Roots	10.2A	6.77B
Festulolium 10 K kg/ha Shoots + 4 K kg/ha Roots	7.41A	10.4A
CV	23.3	26.0
P	0.01	0.01

4. Conclusions

A number of materials used in this study appeared to have the potential to make a favorable structural change when placed in direct contact with the fragipan. Annual ryegrass and Festulolium proved to have the greatest effect. Apparently, these processes are likely due to enhanced solubilization of the fragipan cementing agents by ryegrass and Festulolium root and plant residue exudates [17]. When some humate or limestone materials were combined with AGR there was a significantly greater effect than the ARG alone. Certain humate substances have been shown to facilitate the dissolution of silica-cemented soil aggregates, which are responsible for the rigidity of the fragipans [14] [15] [16] [18]. The positive effect of limestone powder may be an added contribution due to a pH increase that facilitates some of these reactions. Therefore, the use of cover crops and some of these amendments should be encouraged for improving crop yields in some fragipan soils.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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