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Fragipan Remediation Using Annual Ryegrass Cover Crop

Lloyd Murdock*, Tasios Karathanasis, Dottie Call

Department of Plant & Soil Science, University of Kentucky, Lexington, KY 40506, USA
Email: *lmurdock@uky.edu

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Abstract

Field experiments were conducted involving annual ryegrass with and without several surface-applied amendments. The results suggest a significant degradation effect of annual ryegrass on the fragipan horizon. Annual ryegrass (ARG) used as a cover crop was found to degrade previously compacted sections of fragipan, with its roots penetrating through the upper part of the fragipan by first exploring inter-prismatic gray veins and eventually invading adjacent compacted zones, thus creating avenues for additional crop root penetration and utilization of additional water and nutrients. The fragipan structure degradation increased with each (ARG) planting season, resulting in an increasingly deeper soil suitable for crop utilization. Significant crop yield responses of soybean and corn to these soil matrix improvements were observed after the fourth year of using (ARG) as a cover crop and continued to increase yearly thereafter. The yearly addition of sodium, potassium or calcium nitrate fertilizer, or humate additive, did not result in a significant synergistic crop yield effect, but the observed trend in rooting depth warrants further study.

Keywords

Fragipan Soil Horizons, Plant Root Restriction, Degradation of Compacted Sections, Effect of Ryegrass, Root Penetration, Effect of $CaNO_3$, $NaNO_3$, KNO_3, Lime and Humate Surface-Applied Amendments, Soybean-Ryegrass and Corn-Ryegrass Rotations

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 20 million hectares 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 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]-[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 and nutrient uptake at critical growth stages. Plant water and nutrient deficits at reproductive and grain-fill periods may reduce yields by at least 20% - 25% [8]-[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]-[12]. Karathanasis *et al.* [13] used a slaking method and found 3 amendments in addition to annual ryegrass (ARG) that could degrade fragipan clods. Also, Matocha *et al.* [14] reported reduced bulk densities and tensile strengths in fragipan aggregate matrices in fields with a ryegrass (ARG) cover crop compared to those without cover. Murdock *et al.* [10] used an *in-situ* greenhouse method, using intact soil columns, found annual ryegrass (ARG), festulolium and 4 additional amendments that could partially degrade and remediate the fragipan matrix. Previous greenhouse trials with intact undisturbed columns in greenhouse experiments proved that ARG could grow roots into compacted fragipan sections and degrade root-restrictive zones with multiple plantings [15].

In this research approach, ARG was planted in field trials as a cover crop in rotation with a corn and soybean crop. Different past proven amendments [10]-[13] were added to the soil surface to evaluate any possible synergistic effect when used in combination with ARG.

The purpose of this study was to determine the effectiveness and rate of change of ARG and other surface-applied amendments to degrade the fragipan and increase the crop-accessible rooting volume of the soil and its productivity.

2. Materials and Methods

Three studies were established from 2013 to 2015 and were active for 6 to 8 years at the University of Kentucky Research and Education Center in Caldwell County at Princeton, Kentucky. The climate is humid subtropical with about 125 cm of annual rainfall. The studies were conducted on a Zanesville silt loam fragipan soil (fine-silty, mixed, active mesic, oxyaquic fragiudalf) with a 0% - 2% slope. The site was selected because it has a strongly developed fragipan horizon beginning at about 60 cm below the soil surface and is about 50 cm thick. All plot areas were soil sampled yearly to a depth of 15 cm, and fertilizers and lime were added according to the University of Kentucky recommendations found in AGR-1 [16] for the crops grown that year. The organic matter content ranged from 2.6% to 3.0%. Corn (Zea mays) and soybean (Glycine max) were the warm season grain crops and were no-till planted in early May about 4 cm deep at the rate of 75K seeds/ha for corn and 370K seeds/ha for soybeans. The ARG cover crop was no-till planted about the last week in September one cm deep at the rate of 22 kg/ha. The Bounty variety was used the first 3 years, with Marshall being used the remaining years. Weeds were controlled in corn and soybean by preemergent herbicides and multiple in-season applications of glyphosate. ARG was killed in the spring using glyphosate when the ARG was 25 to 30 cm in height and when the weather conditions favored maximum herbicide effectiveness.

The yield response with and without annual ryegrass was analyzed using the Proc GLM (General Linear Modeling) method in SAS Studio (SAS 9.4 Web Browser) (SAS Institute Inc., Cary, NC, USA). Mean separation was performed using the Tukey-Kramer method. The response of soil properties to annual ryegrass treatment was analyzed using a randomized block design with a Mixed procedure in SAS Studio.

The depth to the fragipan in the plot areas was determined prior to the experimental trials using a soil penetrometer, with an average of 27 readings per plot. A 105 cm long hydraulic probe with a 5 cm diameter was used in succeeding years to more closely observe and measure root growth and degradation of the fragipan after the treatments were applied. The plot size in all three trials was 3 m wide and 12 m long. The table below shows some of the measured variability in the depth to the fragipan found in a randomly selected 4.5 m transect within the plot area.

Table 1. Variability of depth to the fragipan from the soil surface along a (short) 4.5-meter transect.

Transect Distance (M)	Fragipan Depth (cm)	Transect Distance (M)	Fragipan Depth (cm)	Transect Distance (M)	Fragipan Depth (cm)
0	60	1.65	57.5	3.30	57.5
0.15	55	1.80	50.0	3.45	67.5
0.30	52.5	1.95	60.0	3.60	50.0
0.45	42.5	2.10	52.5	3.75	60.0
0.60	55.0	2.25	45.0	3.90	65.0
0.75	52.5	2.40	50.0	4.05	62.5
0.90	55.0	2.55	55.0	4.20	57.5
1.05	50.0	2.70	57.5	4.35	65.0
1.20	50.0	2.85	67.5	4.50	67.5
1.35	52.5	3.00	80.0		
1.50	52.5	3.15	75.0		

Range of Depth – 42.5 cm to 80 cm; Average of All Readings – 56.6 cm.

Table 1 shows the significant variance in fragipan depth from the soil surface that occurs naturally on an uneroded soil. The deepest fragipan depth (80 cm) was nearly twice the depth of the shallowest site (42 cm). Measurements to the fragipan depth along a transect of greater length (61 m), also within the plot area, revealed an even greater range of 0.42 m - 0.95 m. The deeper readings tended to occur in clusters. This natural variability should definitely be noted because it will require greater treatment differences to achieve statistical significance for measurements of yield, rooting depths, and depth of fragipan degradation.

Experiment 1: Effect of ARG Cover Crop on Fragipan Degradation and Rooting Depth into the Fragipan for 8 Years

Annual Ryegrass (ARG) has been found to cause matrix degradation in laboratory and greenhouse experiments [9] [10] [13]-[15]. There are no reported scientific studies on the degradation of the fragipan in field trials using ARG as a cover crop. Soil health improvements have been reported on some individual fields [12]. In this scientific study, the main treatment, (ARG), was no-till planted and grown as a cover crop each year prior to the no-till planting of either corn or soybeans. Details of the method are found in the Materials and Methods section. A no cover crop comparison was exactly the same without a cover crop. The study had 5 replications and the treatments were repeated each year for 8 years. Cores (3) were taken from each plot within 5 and 8 years of treatment to observe and record any fragipan degradation, depth to unaltered fragipan, and rooting depth.

Table 2 shows the average depth to the unaltered, consolidated fragipan at the beginning of the trial and 5 and 8 treatment years later. The average depth range of the unaltered fragipan in the untreated control for each of the 3 measurement years is common due to the natural variability as shown in Table 1. The average depth to the fragipan in the ARG-treated plots increased with each year increment, indicating a degradation of the fragipan by the ARG with each treatment year. The measured rate of degradation during the first 5 years was 1.4 cm per year. However, it increased to 3 cm per year over the last 3 years. This increased rate of degradation with increased time was found in other unpublished studies.

Table 2. Average depth to non-degraded fragipan with and without ARG growth over a period of 8 years at three different time periods.

Years of Treatment	Average Rooting and Non-Degraded Fragipan Depth (cm)		
	Treatment		
	ARG	None	P
0	56 a	56 a	NS (0.05)
5	63 b	54 a	0.05
8	72 b	59 a	0.05

Table 3 shows the average minimum and maximum depth to the non-degraded fragipan and rooting in the ARG and non-ARG treatments. Three cores were taken in each plot of the 5 replications for a total of 15 cores. The first measurements were taken prior to beginning ARG treatments. The measure of variability (difference) at the (0 year) trial would be due to the natural variability in depth to the fragipan. The increase in difference (53 cm) associated with the ARG treatments would be due to the uneven degradation of the fragipan by the ARG. The increased variability in depth to the fragipan is probably caused by increased and uneven rooting depth into the inter-prismatic gray veins of the fragipan due to more rapid disintegration (**Figure 1**). Previous research by Murdock *et al.* [15] found deeper and more extensive changes in the inter-prismatic gray veins that were associated with deeper and more extensive rooting. Two of the 15 measurements (13%) had maximum depths greater than the probe depth (105 cm) in the 8-year measurements. At these 2 sites, the soil found in the last few centimeters was of silt loam texture and subsoil characteristics and color, with no fragipan prism fragments, indicating the fragipan at these 2 locations may have been completely degraded. Therefore, the variability of the measurements after 8 years is greater than the 53 cm shown, since the depth of the soil profile without the fragipan is unknown.

Table 3. Maximum and minimum depths to the non-degraded fragipan and rooting depth at three different times over eight years with and without an ARG cover crop in 30 measurements over five replications.

Treatment Year	Rooting and Non-Degraded Fragipan Depth (cm)					
	Treatment					
	ARG			None		
	Minimum	Maximum	Difference	Minimum	Maximum	Difference
0	40-	80	40	42-	85	43
5	42-	95	53	40-	82	42
8	52-	105*+	53+	47-	90	43

No fragipan was found at two core sites, and 105 was the maximum length of the probe.

Figure 1. An exposed fragipan soil showing the inter-prismatic gray veins that separate the consolidated, impermeable prismatic matrix.

Table 4 shows the effect of the cumulative degradation of the fragipan over the 6 years on the yearly yields. Soybeans were grown most years due to the ease of management. However, corn was rotated into the summer crop position occasionally. There were two replicated comparisons within the same approximately 4 ha field. Summer crops were not planted or harvested the 7th year due to a tornado that destroyed the infrastructure and equipment at the Research Center (UKREC). Fall planting of the ARG was able to continue for two additional years.

Table 4. Yield of soybeans and corn with and without annual ryegrass (ARG) cover crop with an increasing number of yearly treatments during the first 6 years.

Years of Treatment	Crop	Yield		P	Difference (%)
		ARG	None		
1	Soybean	64.1	63.8	NS	+0.5
1	Soybean	62.4	62.0	NS	+0.6
1					Average +0.6
2	Soybean	45.8	50.2	NS	−8.8
2	Soybean	68.2	65.5	NS	+4.1
2					Average −2.4
3	Corn	139.1	142.9	NS	−2.7
3	Soybean	60.6	58.3	NS	+3.9
3					Average +1.2
4	Soybean	50.4	47.2	NS	+6.8
4	Soybean	44.2	42.3	NS	+4.5
					Average +5.7
5	Soybean	60.8	57.6	NS	+5.6
5	Soybean	53.9a	47.9b	0.08	+12.5
5					Average +9.1
6	Soybean	49.1	46.3	NS	+6.6
6	Soybean	66.2a	58.7b	0.02	+12.8
6					Average +9.4

The amount of yield in any circumstance is dependent on many contributing factors such as rainfall, temperature, diseases, insects, management capabilities, and others. Depth of rooting is a significant factor, especially in rainfed conditions. Large differences in rooting depth often overshadow the other contributing factors due to higher amounts of plant-available water. This effect is evident in Table 4. There are few differences in yields between treatments with ARG as a cover crop and no cover crop in the first 3 years. There was a small numerical separation in the 4th year. Yield differences in years five and six demonstrate the increased yield potential of the deeper rooting depth. The change in rooting depth is shown in **Table 2**. The fragipan, although deeper, is still present throughout all the plots with the exception of a small area in 2 plots found in the 8th year. The potential yield increase after a drastic degradation of the fragipan is reported in AGR 250 [9]. Two on-farm measurements where ARG has been grown as a cover crop for 10 to 15 years resulted in yield increases between 25% and 60%, depending on the year and crop. In both cases, the rooting depth had increased from about 60 cm to the 1 to 1.2 meter range (unpublished data).

As seen in **Table 5**, the ARG cover crop significantly increased the organic matter in the top 15 cm of the soil. The small numerical increases below 15 cm were not significant and indicate that the additional rooting mass of the ARG cover crop was much less at deeper soil depths, but it was effective in breaking down parts of the compacted fragipan matrix.

Measurements of phosphorus, potassium, calcium, and magnesium made at the same depths as the organic matter in **Table 5** also indicate no accumulation of these nutrients above that found with no cover crop treatment.

Table 5. Effect of 7 years of ARG cover crop on the soil organic matter content at increasing depths.

Depth (cm)	Organic Matter (5)		
	ARG	None	P*
0 - 15	3.01b	2.87a	0.05
15 - 30	2.75a	2.21a	NS
30 - 45	2.00a	1.99a	NS
45 - 60	1.93a	1.93a	NS

*Significance at 0.05 level or less.

Experiment 2: Effect on ARG and Some Common Agricultural Fertilizers on Fragipan Degradation in Field Trials after Seven Growing Cycles Using ARG as a Cover Crop with a Soybean or Corn Rotation

ARG, sodium nitrate ($NaNO_3$), and materials that raise pH, such as finely ground calcium carbonate, have been reported to partially degrade the fragipan when placed in direct contact with the fragipan [9] [10] or when $NaNO_3$ is placed on the soil surface with a growing ARG cover crop in the greenhouse [15]. One objective of this experiment was to determine any synergistic effects of these fertilizers on changing the brittle fragipan matrix when placed on the soil surface while growing ARG as a cover crop and a corn or soybean summer crop under field conditions. Another objective was to evaluate if some basic nitrate (NO_3)-based fertilizers would leach sufficiently to raise the pH of the fragipan layer and provide a more favorable rooting growth environment under rainfed field conditions. All crops and cover crops were planted using no-tillage.

The fertilizer treatments used were sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3), and calcium nitrate ($CaNO_3$). Urea was used as the nitrogen source in the control treatment, which had no cover crop and only the corn or soybean summer crop. Nitrogen was not applied to the ARG cover crop, but 224 kg/ha of N was applied to the summer crop (corn or soybeans) and used as a control treatment. Seven complete cycles were completed over seven years. Each treatment had four replications.

Using ARG as a cover crop, plus the three different fertilizer treatments, resulted in an average of 11.4 cm increase in depth of rooting and soil depth above the hard unaltered fragipan (**Table 6**). These are very similar to the yearly depth increases found in Experiment 1. There appears to be no synergistic effect by any one fertilizer over the others in the rate of fragipan degradation. The synergistic effect of adding $NaNO_3$ to an ARG cover crop rotation reported by Murdock [15] using intact complete soil profile cores in the greenhouse was not apparent in this field study.

Table 6. Average rooting and non-degraded fragipan depth (cm) after 7 years of ARG cover crops and selected fertilizer treatments.

Treatment	Depth (cm)
Control (urea)	59.5b**
Sodium Nitrate + ARG	72.0a
Potassium Nitrate + ARG	69.8a
Calcium Nitrate + ARG	70.1*a

*One site had only remnants of the fragipan remaining; **Probability of significance was 0.05 or less.

Except for the 0 - 15 cm depth, the pH was similar for all nitrogen sources at each sampling depth (**Table 7**). The lower pH in the 0 - 15 cm depth in the control was probably due to the acidifying effect of the nitrification of the ammonium that develops from urea.

Table 7. Effect of soluble nitrate fertilizers on the soil pH of the top 45 cm after 7 years of additions of nitrogen at the rate of 225 kg/ha per year.

Treatment	Soil pH					
	Depth (cm)					
	0 - 15	P*	15 - 30	P*	30 - 45	P*
Control	5.8a	0.05	6.6a	NS	5.0a	NS
Sodium Nitrate	6.4b	0.05	6.6a	NS	5.1a	NS
Potassium Nitrate	6.6b	0.05	6.8a	NS	5.3a	NS
Calcium Nitrate	6.4b	0.05	6.5a	NS	5.3a	NS

*Probability sensitivity at the 0.05 level.

The lack of synergistic effects in the field trials compared to the greenhouse experiments, involving intact soil cores encased in plastic tubes, may be attributed to some leakage occurring along the edge of the soil/core-plastic interface under greenhouse conditions. The leaching is speculative but is a possibility, as noted by Murdock, author of citation [10]. Obviously, this leaching mechanism would not be available under natural soil conditions. Also, adding soluble nitrate nitrogen fertilizers without ammonium appeared to have little effect on the pH except in the surface 0 - 15 cm layer. Therefore, it would be difficult to have a synergistic effect on the fragipan degradation by planting ARG as a cover crop without using an amendment compound that would be capable of leaching through the soil profile at a relatively high rate.

Experiment 3: Effect of ARG and Menifee Humate on fragipan degradation in field trials after six growing cycles using an ARG cover crop with a soybean or corn rotation

Humates have been reported to degrade the fragipan when placed in direct contact with the fragipan [9] [10]. The objective of this trial was to determine the effectiveness of Menifee humate to degrade the fragipan when placed on the soil surface in a no-tillage environment. This humate was also evaluated for any synergistic effect it might have when placed on the soil surface with ARG as a cover crop. The Menifee humate is a sub-bituminous material commonly used as a soil conditioner. In this experiment, it was surface-applied just prior to the ARG planting each fall at the rate of 560 kg/ha. The trial was continued for six years. Each treatment had four replications.

Table 8. Average rooting and non-degraded fragipan depth (cm) after 6 years of ARG cover crop, humate, and combination treatment.

Treatment	Depth (cm)
Control	65.3b*
ARG	70.0a
Humate	66.0b
ARG + Humate	73.3a

*Significance at the 0.05 level or lower.

As seen in **Table 8**, the depth to the non-degraded fragipan and rooting depth in the control treatment and the humate treatment were almost identical. The ARG treatment and the ARG + Humate treatment were statistically the same, even though the combination of ARG and humate was numerically greater. This indicates that the surface-applied humate was probably not able to move through the profile over a six-year period to have any significant effect on the degradation of the fragipan. This is further supported by the fact that there was little, if any, difference between the control treatment and the humate treatment. This trial further substantiates the effectiveness of ARG even without the addition of other amendments. Even the highly soluble sodium nitrate fertilizer used in Experiment 2 did not have sufficient leaching capabilities to substantially increase the rate of fragipan degradation above that of ARG alone.

3. Conclusion

The results of this study suggest that the use of ARG can effectively remediate the fragipan in field conditions, particularly over a period of several years. When ARG was used as a cover crop in rotation with corn or soybeans, the degrading effect of the ARG on the fragipan was a continuous process that occurred with each crop of ARG and averaged 1.4 cm per year for the first 5 years and increased to 3 cm per year for the last 3 years of the 8-year study. The result is a structural change of the fragipan from a nearly massive compacted matrix to a more porous, blocky, or granular structure, which is similar to a regular subsoil in structure and color. The rate of degradation appears to accelerate with time due to the increased rate of degradation in the inter-prismatic gray veins by the more vigorous ARG roots. The pressure applied by the ARG roots can break sections of the fragipan matrix into smaller segments. The crop roots can take advantage of those cracks to expand their rooting system, and when the ARG is not active, they use the openings created by their roots to extend theirs and improve water and nutrient uptake. The crop yields increase as the soil deepens with each additional annual grass cover crop. Breakdown was sufficient in 5 to 6 years to significantly increase yields of corn and soybeans by about 10 percent. The yields can increase by 30% or greater based on farm field measurements. Amendments ($NaNO_3$, KNO_3, $CaNO_3$, and humate), which had previously shown to potentially increase the degradation rate of the fragipan when applied to an ARG treatment in the greenhouse, were not effective under field conditions.

Conflicts of Interest

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

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