

Fragipan Soil Changes with Growth of Annual Ryegrass and Festulolium with Surface Applied Amendments

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Abstract

A greenhouse experiment was conducted involving complete/intact 100 cm cores of a fragipan soil. The cores were maintained in moist conditions throughout the experiment as annual ryegrass (*Lolium multiflorum*) or festulolium (*Lolium* spp and *Fescue* spp hybrid) were grown with and without additional surface applied amendments, including NaF, NaNO₃, NaCl, and KCl. The results suggest a significant effect of annual ryegrass and festulolium on fragipan horizon degradation after 24 months. Annual ryegrass and festulolium were found to effectively change the structure of the fragipan horizon when planted on the soil surface and roots grew through the upper soil profile and penetrated into the fragipan. The fragipan structural change (degradation) appeared to increase with each planting sequence, particularly with soybean crop rotations. Sodium nitrate added to the soil surface with the growth of annual ryegrass resulted in a significant synergistic effect for degrading the fragipan horizon. The other amendments were not as effective in causing additional fragipan degradation.

Keywords

Fragipan Soil Horizons, Plant Root Restriction, Degradation of Compacted Sections, Effect of Ryegrass and Festulolium, Root Penetration, Effect of NaF, NaNO₃, NaCl, KCl Surface Applied Amendments, Soybean-Ryegrass and Soybean-Festulolium 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

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 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 are 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]-[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]-[11]. Karathanasis *et al.* [12] used a slaking method and found 3 amendments in addition to annual ryegrass (ARG) that could degrade fragipan clods. Also, Matocha *et al.* [13] 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 that found annual ryegrass (ARG), festulolium and 4 additional amendments that could partially degrade and remediate the fragipan.

The approach used in this study utilized complete, intact, fragipan soil cores with annual ryegrass or festulolium grown in rotation with soybeans. Different past proven amendments were added to the soil surface to evaluate their effectiveness to accelerate the degradation of the fragipan in combination with the annual ryegrass or festulolium. The trials took place over a 24-month period in the greenhouse of the University of Kentucky Research and Education Center at Princeton, Kentucky. The purpose of this study was to determine, in green house experiments, the relative effectiveness and rate of degradation of fragipan horizon sections by different plants and amendments, applied on the surface of field-sampled, undisturbed and intact fragipan soil cores

2. Materials and Methods

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 5-cm diameter transparent plastic sleeve to a depth of 100 cm, which was the lower depth of the fragipan horizon. All cores were collected within a radius of 6 meters. The topsoil was tested for needed nutrients by the University of Kentucky soil testing laboratory and the nutrients were added as recommended. The top 7.5 cm were tilled manually to incorporate any needed fertilizer and lime. Also, surface-applied amendments were added at this time and water was added to moisten the

soil. After the cores dried to allow tillage, seeds of annual ryegrass (5/core) were planted 1.25 - 2.5 centimeters deep. The soil was kept moist and the grown ryegrass was killed with glyphosate about 3 months after planting (seed head appearance). When soybeans were a part of the treatment planting rotation, two seeds per core were planted about 2.5 centimeters deep and harvested about three months after planting. Any succeeding plantings were accomplished similar to the first plantings. Control cores were kept moist. The following plant-amendment combinations were used in 3 different experiments. 1) Control, ARG, ARG+NaF; 2) Control, ARG, ARG + NaNO₃, ARG + KCl, ARG + NaCl + KCl in a ryegrass-soybean rotation and 3) Control, ARG, Festulolium. Each treatment was replicated three times. After the last harvest, cores were sectioned vertically in half to allow a thorough examination of changes in the soil matrix and root growth patterns.

Penetrometer measurements were also made in the first experiment using a 5-mm diameter pointed penetrometer while applying 620 kPa of pressure. The depth of penetration was measured prior to the first treatments and again after trial completion prior to dissecting the cores to determine depth changes of strength, hardness and structure of the fragipan. Visual examination also helped verify the depth of structural changes in the fragipan from the evidence of greyer bleached matrix zones and more friable flaky soil aggregate-particles. The rooting depth of the annual ryegrass was also recorded.

3. Results and Discussion

Experiment 1: Early effects of annual ryegrass after 2 growing cycles on a fragipan soil matrix with and without sodium fluoride

Annual ryegrass (ARG) and Sodium Fluoride (NaF) have been found to cause fragipan matrix degradation [9] [10] when placed directly on the fragipan. The objectives of this experiment were to identify any potential early degradation effects of these two treatments on the fragipan horizon when ARG is grown on the soil surface for two seasons and the sodium fluoride is surface applied. The treatments in this experiment included the control (no treatment), annual ryegrass and annual ryegrass plus NaF at a rate of 127.8 kg/ha.

A shallow soil profile should allow a more rapid rooting to the fragipan as well as a reduced time of sodium fluoride leaching to the fragipan. This should also provide a more rapid display of any possible effects of these two treatments on the fragipan. Therefore, the soil profiles, for this trial only, were intentionally truncated by removing all the soil above the fragipan and then replacing only 20 cm of the removed topsoil on top of the fragipan. Annual ryegrass was planted on top of these cores and sodium fluoride was added according to treatment specifications (previously described) on September 17, 2013. After about 3 months the annual ryegrass was harvested, and a second planting of ARG and sodium fluoride application occurred on January 29, 2014. The cores were kept moist throughout the experiment, with three replications for each treatment. The trial was terminated on June 4, 2014 after 2 treatment cycles. The depth of penetration was

measured with the penetrometer at the start and at the end of the experiment. The cores were then dissected, and observations and measurements were made. The depth of rooting into the fragipan was measured from the top of the fragipan prior to treatment as marked on the plastic cylinder containing the soil core. Visual examination also helped verify the depth of structural changes in the fragipan from the evidence of greyer bleached matrix zones and more friable flaky soil aggregate-particles.

Figure 1 shows the variable distribution of interprismatic gray veins in an exposed fragipan soil profile. Each sampled core usually had a different amount and distribution of these veins. This characteristic may cause significant variability of treatment effects on each core. In spite of this variability, there were definitive visible signs of additional degradation and expansion of the bleaching veins, particularly after 2 treatment cycles, as can be seen in **Figure 2**. Small, bleached unconsolidated soil particles are also evident along with a less consolidated soil structure.



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



Figure 2. Visual signs of fragipan degradation by ARG + NaF (right core), compared with untreated fragipan (left core).

The dissected cores, after 2 treatment cycles, revealed that the ARG was as effective as the combination of ARG with NaF. There was significant annual ryegrass rooting in the top 3 to 5 cm of the fragipan that resulted in a mostly uncemented structure and bleaching of small soil particles in the inter-prismatic gray veins (**Figure 2**). These observations were also supported by the penetrometer measurements (**Table 1**). Rooting was more abundant in the gray areas where significant bleaching occurred, and small individual soil particles were present.

Below the top 3 - 5 cm of the original fragipan, roots were found entirely in the inter-prismatic gray veins of the fragipan soil cores. The deepest rooting depth penetration by ARG occurred after 2 treatment cycles, particularly in more bleached and grayish structural inter-prismatic degradation areas (**Table 2**). This corroborates with early preliminary field trials, indicating that the bleaching of the fragipan inter-prismatic gray veins was more common on succeeding plantings of ARG. Therefore, the unbleached areas with rooting may have been the first rooting stage effect of the ARG treatment. There is no indication that the addition of NaF was beneficial to the rooting penetration depth of the ARG. The depth to which the roots grew into the fragipan varied greatly between replications within the same treatment. The depth of growth was probably largely dependent on the depth of the preexisting gray vein in that particular core. Previous studies found NaF to be effective when placed directly on the fragipan [10]. To be effective in this study, the NaF must leach through the upper soil profile to the fragipan in a timely manner. It also had little or no nutritional value to encourage additional rooting.

The fragipan varies over short distances so the results will be more variable than some trials. However, sufficient replications and the great effectiveness of

Table 1. Soil depth penetration to the non-degraded fragipan as measured by penetrometer.

Treatment	Penetration Depth (cm)	
	Before TMT	After TMT
TMT		
ARG	20.3 ^a	22.9 ^a
ARG + NaF	20.3 ^a	22.4 ^a
Control	20.3 ^a	20.8 ^b
P	NS (0.05)	0.05

Resistance before and after two plantings of ARG with and without NaF.

Table 2. Average maximum depth of ARG rooting into the fragipan after two growing cycles with and without NaF (3 replications).

Treatment	Depth (cm)
ARG	29.2 ^a
ARG + NaF	13.6 ^a
P	NS (0.05)

ARG were enough to statistically prove the effectiveness of ARG.

Experiment 2: Effect of ARG and some common agricultural fertilizers on fragipan degradation in greenhouse fragipan soil cores after several growing cycles using an AGR/soybean rotation

Annual ryegrass, as well as some common fertilizers, have proven to degrade the fragipan when placed in direct contact with the fragipan [9] [10]. One of the objectives was to determine the effectiveness of these fertilizers to change the fragipan when placed on the surface of a complete soil profile in the greenhouse. Another objective was to evaluate any possible synergistic effects of the different fertilizer additives when used in combination with growing annual ryegrass. The annual ryegrass was grown and harvested six different times, which allowed for an evaluation of its effectiveness with longer term treatments. Soybean plants were grown after each annual ryegrass cycle to simulate what might happen in a yearly soybean crop with an annual ryegrass cover crop.

The 100 cm soil profile cores were collected inside 5-cm diameter plastic sleeves and prepared as previously described in the beginning methods section. The individual treatments are listed in **Table 3**.

Table 3. Treatments used in experiment 2.

Treatments

1. ARG plus NaNO₃ (Sodium Nitrate) 224 kg/ha at each ARG planting.
 2. ARG plus KCl (Potassium Chloride) 560 kg/ha, total added during first planting.
 3. ARG plus KCl (Potassium Chloride) 1120 kg/ha, total added during first planting.
 4. ARG plus NaCl and KCl (Sodium Chloride and Potassium Chloride) 280 kg/ha each, total added during first planting.
 5. ARG
 6. Control, Fescue, 20 plus years as taken from collection site.
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The trial began June 2014. Half of the NaNO₃, KCl 500, NaCl/KCl and one-third KCl 1000 treatments were added and mixed into the top four inches of the profile. The moisture was kept at about field capacity for two weeks to disperse salts. Bounty annual ryegrass was planted and the second fertilizer split was added one month after planting. The third KCl 1000 split was added two weeks later. No salt damage was observed. Urea at 224 kg/ha/planting was the nitrogen source for all ARG treatments except the NaNO₃ treatment. The ARG was planted about 1 cm deep and harvested about 3.5 months later with soybeans planted about 2 weeks later and harvested about 3.5 months later. The cores were kept moist to allow good plant growth. Each treatment had 3 replications. The trial was terminated November 2018 after 6 plantings of annual ryegrass and 4 plantings of soybeans. The cores were dissected and analyzed for color and soil structure changes, root growth, extractable K and Na, pH and bulk density. The cores were analyzed in 5 cm sections beginning at the top of the original fragipan as marked on the

plastic sleeve at the time of soil core extraction. The depth of root penetration and of any structural change was measured. A close estimate of the percentage of soil volume that underwent a structural change in each 5 cm section was made.

Figure 3 shows the change in soil structure and color that occurred after 6 plantings of annual ryegrass. The structure changed from a massive, cemented structure that prevented root growth and water movement to a more porous structure that allowed root growth and water movement. As seen in **Figure 3**, most of the root growth and structural change occurred near the top of the fragipan where more reoccurrence of rooting was prevalent with each succeeding annual ryegrass growth cycle. Near the lower part of the fragipan shown in **Figure 3**, the change in the fragipan is found mainly in narrow passage ways where the annual ryegrass roots probably found less resistance for growth into the fragipan. The top part of the fragipan (14 cm from top of the original fragipan to the white pencil marker) was changed to a subsoil like horizon that allowed extensive rooting.

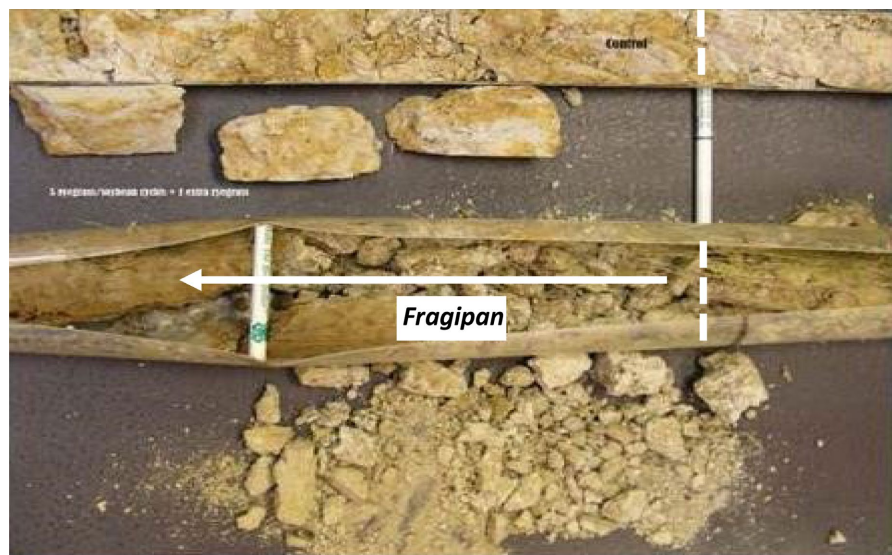


Figure 3. Altered fragipan (lower soil core) after ARG is grown six times in an annual ryegrass/soybean rotation compared to the control (upper soil core).

Table 4 shows depth to which a soil structural change occurred within the fragipan as affected by each fertilizer additive in combination with annual ryegrass compared to annual ryegrass only and an untreated control. Except for the control, all treatments were effective in changing the soil structure. The NaNO_3 /ARG treatment had a significantly greater depth of structural change than the other treatments. The other annual ryegrass chemical combinations were not significantly different than the annual ryegrass treatment alone. This seems to indicate that KCl and NaCl/KCl additives have a limited synergistic effect, and that most of the fragipan matrix degradation occurs through the rooting penetration of the ARG. NaNO_3 was readily leachable and offered nutritional value to encourage additional rooting. Also, 20 plus years of fescue growth did not appear to have any noticeable effect on the degradation of the fragipan.

The NaNO₃ treatment appeared to have the best synergistic effect, probably due to rapid movement through the soil profile and the growth enhancement from the nitrogen addition.

Table 5 shows the amount of structural change (on a volume basis) that was found in the top 15 cm of the fragipan. All treatments were similar in the amount of structural change that took place. Annual ryegrass without any of the additives was similar to those with additives, even NaNO₃, that had previously been found to induce fragipan degradation. These trends may indicate that annual ryegrass, probably due to root secretion of active compounds, has a greater potential than any of the additives tested to degrade the fragipan. However, since the effect of NaNO₃ structural change went much deeper than 15 cm into the fragipan than any of the other treatments (**Table 4**), the total volume of structural change is 20% greater for the combination of NaNO₃ and annual ryegrass, when that additional area is included. Therefore, a synergistic effect of ARG and NaNO₃ in enhancing fragipan degradation is possible.

The rate of positive structural change was at a rate that would be expected to

Table 4. Effect of six annual ryegrass—soybean rotational cycles (ARG/SB) in combination with different chemical additives on the depth of soil structural change into the fragipan.

Plant Rotation	Chemical Additive	Depth of Change (cm)
ARG/SB	NaNO ₃	27.1 ^a
ARG/SB	KCl 560	14.4 ^b
ARG/SB	KCl 1121	18.6 ^b
ARG/SB	NaCl/KCl	14.7 ^b
ARG/SB	None	17.8 ^b
Fescue Sod*	None	2.8 ^c
P		0.0013

*As removed from soil with 20 plus years of fescue sod.

Table 5. Effect of six annual ryegrass—soybean rotational cycles (ARG/SB) in combination with different chemical additives on the % degraded fragipan portion by volume.

Plant Rotation	Chemical Additive	Degraded Portion (%)
ARG/SB	NaNO ₃	58 ^{ab}
ARG/SB	KCl 560	68 ^a
ARG/SB	KCl 1121	52 ^{ab}
ARG/SB	NaCl/KCl	42 ^b
ARG/SB	None	60 ^{ab}
Fescue Sod*	None	16 ^c
P		0.010

*As removed from soil with 20 plus years of fescue sod.

make a useful difference in crop production. Six cycles of ARG increased the rooting volume of the soil by 18%. Considering, the untreated soil had 60 cm of rooting depth above the fragipan. The addition of NaNO_3 resulted in a 26% rooting volume increase.

Table 6 shows the extractable K and Na content in the top 5 cm of the fragipan. The K content is higher in the 3 treatments containing K, suggesting that some of the applied K is being leached through the upper soil profile into the fragipan. However, this amount is only 17% higher than the average K concentrations found in the non-KCl treatments.

The average Na content (**Table 6**) is 98% higher in the top of the fragipan with the 2 treatments containing sodium than the average of the other treatments. This indicates that the Na compounds are readily leached through the profile to the fragipan. Sodium nitrate and sodium chloride appeared to be equally leachable. However, NaNO_3 degraded the fragipan to a significantly deeper depth (**Table 4**) than the NaCl/KCl treatment. The long term use of these salts may lead to excessive salinity issues in some situations.

Table 6. Extractable potassium and sodium in the top 5 cm of fragipan with different treatments placed on the surface of a complete soil profile in the greenhouse after a rotation of 6 plantings of annual ryegrass and 5 plantings of soybeans (ARG/SB).

Plant Rotation	Chemical Additive	Extractable K (ppm)	Extractable Na (ppm)
ARG/SB	NaNO_3	71	183 ^a
ARG/SB	KCl (Low)	92	110 ^{bc}
ARG/SB	KCl (High)	90	120 ^b
ARG/SB	NaCl/KCl	87	202 ^a
ARG/SB	None	75	106 ^{bc}
Fescue Sod*	None	83	54 ^c
P		NS (0.05)	0.0024

*As removed from soil with 20+ years of growing fescue sod.

Table 7 shows the water pH of the soil in the top 5 cm of the fragipan. The range of pH readings was between 4.0 and 4.6, suggesting no significant pH increase at the top of the fragipan over these 6 application times. Therefore, a pH increase in the fragipan was not the reason for the higher amount of structural changes in the fragipan with the annual ryegrass/ NaNO_3 treatment.

The root growth of annual ryegrass into the fragipan with a very low pH suggests that low pH is not a major factor for the absence of root growth into the fragipan.

Experiment 3: Comparison of the effectiveness of growing annual ryegrass and festulolium to degrade the fragipan horizon

In early laboratory trials, by these two authors, many plants (wheat, rye, corn, soybeans, brassicas, clovers and fescue) were tested for any effectiveness to

Table 7. pH in the top 5 cm of a fragipan in greenhouse soil cores sampled from a fragipan soil receiving different surface treatments after a rotation of 6 plantings of ARG and 5 plantings of soybeans (ARG/SB).

Plant Rotation	Chemical Additive	Soil pH
ARG/SB	NaNO ₃	4.2
ARG/SB	KCl (560)	4.0
ARG/SB	KCl (112)	4.3
ARG/SB	NaCl/KCl	4.1
ARG/SB	None	4.3
Fescue Sod*	None	4.1
P		NS (0.05)

*As extracted from 20 plus years of fescue sod.

degrade the fragipan (unpublished). Festulolium was the only plant besides ARG to degrade the fragipan. Annual Ryegrass has been found to degrade the fragipan [9] [10] [12]-[14]. Some festulolium varieties are hybrids of fescue and annual ryegrass [10] [12]. Festulolium has been found to change the fragipan when placed in direct contact with it [10]. This trial compared the effectiveness and rate of change of the fragipan horizon by the two different grass species when grown as a crop.

The treatments involved a) ARG (Bounty variety), b) Festulolium (5563A) variety, and c) control.

Soil cores of complete profiles were collected as previously described. A seedbed was tilled by hand in the top 2.5 cm of the soil profile core. The cores were planted with 6 seeds of each species about 1 cm deep and watered until moist. About 3.5 months later, at initial heading, the plants were killed with glyphosate, top growth was clipped and removed and the top 1 cm of the soil core was prepared for the next planting. Three growth cycles were completed on the three replications. After the third cycle was completed, the cores were dissected and examined for altered fragic properties, as well as structural changes and rooting by depth, above the solid, unaltered portion of the fragipan. The amount of structural change in each core was estimated at each 2.5 cm incremental depth. The top of the original unaltered, consolidated fragipan was assumed to be the depth where a significant amount of fragipan prisms were mixed in an unconsolidated porous structure with rootings.

Table 8 shows the depth to which rooting of each grass changed the soil structure from a dense consolidated structure to a more porous structure with some small fragic prisms. This structural change is similar to that seen in the image in **Figure 3** in Experiment 2. The depth to which structural change occurred between the replications within each species was variable. However, the average depth of each of the two species was quite similar. The differences between replications were probably related to the amount and depth of interprismatic grey veins.

Table 8. Depth of structural change from the top of the original fragipan to the unaltered fragipan after 3 continuous plantings of ARG and festulolium.

Treatment	Depth Change (cm)
Annual Ryegrass	17.0a
Festulolium	15.3a
Control	0.8b
P	0.0114

Table 9 shows the amount (%) of structural change (on a volume basis) that was found in the portion of the fragipan where rooting was present. The amount of the fragipan core change between the replications within each species varied considerably. However, the average value of the replications was close to 50 percent for both annual ryegrass and festulolium. Observations made through the transparent plaster liners during the three plantings show obvious color and some structural changes within the matrix. These changes for both species were very similar. The early bleaching effect during the initial stages of structural change were evident in both species. Within weeks, the bleached color changed to a color very similar to the lower portion of the subsoil in both species.

Table 9. The portion of the fragipan core (volume) showing soil structural changes within the affected depth shown in **Table 8**.

Treatment	Degraded Portion (%)
Annual Ryegrass	52.1 ^a
Festulolium	48.8 ^a
Control	10.0 ^b
P	0.0226

4. Conclusions

The results of the 1st experiment suggest that ARG has the ability to degrade the fragipan over time. Two plantings of annual ryegrass changed the soil structure in the top 2-3 cm of the fragipan. There was a partial change below this level. The deeper change was confined to the interprismatic gray veins that separated the prism areas. Annual ryegrass roots were found in these areas which caused bleaching and smaller soil particles that would be easily broken apart. The process begins with roots growing into the gray veins of the fragipan and slowly changing the surrounding compacted area into a more friable soil structure and rooting medium. It appears that the inter-prismatic gray veins are the avenues of the least root resistance that give the ryegrass roots a foot-hold for a greater degradation of the adjacent compact fragipan matrix with continuing ARG growth.

Although ARG rooting is the dominant means of effectively changing the structure of the fragipan, our study showed that certain surface applied amendments,

such as sodium nitrate placed on the surface of the profile in combination with growing annual ryegrass had a significant synergistic effect in the fragipan degradation process. This occurs most likely through the increased dispersibility of Na and the easy leaching of the nitrates contributing to a larger rooting mass volume. The other tested chemicals had little or no effect on degrading the fragipan when they were applied directly on the surface of the profile. The results also showed that the low fragipan pH may have little overall effect on preventing root growth into the fragipan matrix.

Our experiments also indicated that both ARG and *Festulolium* possess similar capability characteristics of rooting into a fragipan matrix and through several plantings, could change the fragipan into a more porous structural medium, capable of supporting root growth and improving yields.

The degradation rate by these two grass species was surprisingly rapid at 15 - 16 cm of depth over 3 growth cycles. The average thickness of the fragipan in many fragipan soils is about 60 cm, implying it is possible that some of these practices can overcome their harmful effects on crop growth.

In addition to degrading the fragipan, multiple years of an ARG cover crop also increases soil organic matter, water infiltration, reduces erosion potential and scavenges residual nitrogen.

Research, to be published, and information in AGR 250 [9] demonstrate the results can be translated to field conditions.

Conflicts of Interest

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

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