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Soil Health in American Sports Fields

Miria C. Barnes

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Soil Health in American Sports Fields

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Healthy soils are essential for sustaining the world's ecosystems and maintaining human lifestyles. The adoption of biological, chemical, and physical analyses to assess soil health is a relatively new concept with a paucity of scientific work assessing how these metrics are affected by field management in urban systems Soil samples (n = 110) were collected from a diverse range of sports fields and, for comparative purposes, golf courses, farm fields, non-sport urban, undisturbed forest, and non-vegetated sandy soils. The samples were then analyzed using biological, chemical, and physical metrics to determine if there were significant differences between sport/golf venues and non-sport/golf soils. Soil health measurements included total organic carbon (TOC), organic matter (OM), permanganate oxidizable organic carbon (POxC), total inorganic carbon (TIC), potentially mineralizable nitrogen (PMN), carbon respiration (CO_2), β-glucosidase (BG), autoclave citrate-extractable (ACE) protein, and aggregate stability (AS). All soils that supported vegetation had higher soil health test values than the non-vegetated sandy soils. In general, differences were either minimal or not detectable between sports field soils and other soils. Notably, golf venues demonstrated higher CO_2 and BG than sport venues, while TOC and OM levels in sports fields and golf courses were similar to unmanaged, urban, and farm systems. In addition, ACE protein levels were notably higher in forests. The fertilized venues were generally higher for the less mobile nutrients with poor solubility (P, Zn, Fe, Mn, Cu) and lower in pH than the sand control. Somewhat surprisingly, the non-fertilized forest was generally equivalent to the fertilized venues in nutrients Sports fields had ample soil fertility and reasonable pH and EC, although they had excessively high soil P concentrations. Correlations between soil properties were performed and statistical differences were analyzed using Analysis of Variance and Tukey-Kramer mean separation. Biological and physical soil properties were highly correlated with each other, and overall, biological activity was similar across all land uses, including sports fields. In general, nutrient concentrations and EC were positively correlated, but tended to decline with increasing sand content. The data collected, and comparisons made, will add to scientific and community understanding of soil health as a function of land management.

Keywords: soil health, sports fields, golf course, management

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CHAPTER 1

A Comparative Evaluation of Soil Health Using American Sports Fields

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ABSTRACT

Sports fields are among the most intensively managed soils, especially with respect to pesticide and fertilizer application. The primary objective of this study was to compare soil health in sports field soils with other less intensively managed soils. Soil samples (n = 110) were collected from a diverse range of sports fields and, for comparative purposes, golf courses, farm fields, non-sport urban, undisturbed forest, and non-vegetated sandy soils. Soil health measurements included total organic carbon (TOC), organic matter (OM), permanganate oxidizable organic carbon (POxC), total inorganic carbon (TIC), potentially mineralizable nitrogen (PMN), carbon respiration (CO_2), β-glucosidase (BG), autoclave citrate-extractable (ACE) protein, and aggregate stability (AS). All soils that supported vegetation had higher soil health test values than the non-vegetated sandy soils. In general, differences were either minimal or not detectable between sports field soils and other soils. The TOC, POxC, PMN, CO_2, and BG averages in sports fields were 11 mg g^{-1}, 333 mg kg^{-1}, 82 mg kg^{-1}, 0.062 mg, and 63 mg kg^{-1} h^{-1}, respectively. These values were similar to soils under turfgrass or other vegetation, with averages of 19 mg g^{-1}, 446 mg kg^{-1}, 105 mg kg^{-1}, 0.083 mg, and 108 mg kg^{-1} h^{-1}, respectively. All soil health values were significantly higher in vegetated soils relative to soils with no vegetation, which averaged 2.4 mg g^{-1}, 81 mg kg^{-1}, 4.2 mg kg^{-1}, 0.021 mg, and 53 mg kg^{-1} h^{-1}, respectively. Notably, golf venues demonstrated higher CO_2 and BG than sport venues, while TOC and OM levels in sports fields and golf courses were similar to unmanaged, urban, and farm systems. In addition, ACE

protein levels were notably higher in forests. Biological and physical soil properties were highly correlated with each other, and overall, biological activity was similar across all land uses, including sports fields. The results of this study will aid the scientific community and improve public understanding of soil health as a function of land management.

INTRODUCTION

Healthy soil is essential for global sustainability (Hillel 1992). Soil improvement, through fertilization etc., was an important part of the Green Revolution that ushered in steadily increasing yields (Hopkins and Hansen 2019). This has fueled increases in human lifespan and improvements in quality of life. However, environmental degradation and economic losses are some of the serious issues that can arise from mismanaged terrestrial soil-based ecosystems and have resulted in the study of soil health (Landrigan et al. 2018). While it is not a new concept, soil health is the focus of increasing attention in agricultural conversations and research (Hopkins et al. 2023). Doran (1996) defined soil health as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans” and this definition is used by the Natural Resource Conservation Service (NRCS) as well as other public and private soil health initiatives. Assessment of soil health is accomplished through a variety of measures, including biological, physical, and chemical soil properties.

Intense management of agricultural and urban landscape soil is speculated to contribute to the depletion of soil health characteristics in some circumstances (Amundson et al. 2015). For example, soil microbial communities and water infiltration/percolation can be disrupted by soil disturbances, such as tillage (Guo and Gifford 2002). Although fertilizers and pesticides are important components of the Green Revolution, these are increasingly scrutinized as contributing to the decline of soil health (Hobbs et al. 2008).

Similar to medicines designed to control bacteria and fungi (*e.g*., penicillin and tolnaftate) in support of human and animal health, pesticides are designed to control pests (*e.g*., bactericides and fungicides that target harmful microorganisms). In contrast, fertilizers are not intended to reduce pest populations but, rather, to provide the essential nutrients for plant health (Hopkins 2020). However, even nutrients and pesticides can be toxic at high dosages (Hopkins 2019). Although pesticides and fertilizers are used extensively in agriculture, golf courses and sports fields are arguably the most intensively managed soil systems in the world, including application of fertilizers and pesticides (Gillette et al. 2016, Liu et al 2011, Streeter and Schilling 2018). Because of such intensive management, sports fields are a unique case for the evaluation of soil health indicators.

We hypothesize that sports field soils are healthy in the framework of standard soil health measurements, and exhibit biological, physical, and chemical characteristics that are similar to other land use types and in line with conditions required for plant growth. The objectives of this study were to: (1) measure soil properties related to soil health and compare the soil properties between sports fields and sports fields type (collegiate and professional), as well as with the comparative unmanaged soils, (2) determine the correlation between soil health properties, (3) compare soil health in painted and non-painted grass areas in American football fields, (4) verify that deep freezing of soil samples does not negatively impact soil health measurements.

MATERIALS AND METHODS

Sampling

Soil samples (n = 110, Supplemental Table 1-1a-e, Fig. 1-1) were collected between September 2021 and April 2022 from various sports fields, as well as golf courses, farm fields, non-sport urban landscapes, undisturbed native forest soils, and sandy soils without vegetation (desert, beach, and golf course sand bunkers). The samples represent a diversity of geographical conditions (Fig. 1-1). The sports field samples represent a diversity of facility types (municipal, primary/secondary K-12 schools, collegiate, and professional). These represent American football, American soccer (internationally known as "football"), baseball, softball, and multi-sport intermural fields.

In eight of the American football fields, additional soil samples were taken from areas where team logos had been painted on the turfgrass multiple times each season to compare the soil health in non-painted areas. Additionally, in five American sports fields, an additional soil sample was taken that would not be stored in a freezer with the rest of the samples. This was done to ascertain the difference between storing samples in a frozen state versus sampling close to the time of processing without freezing to determine if the ultra-cold temperatures would impact the test results.

One sample was taken per field, except for fields that had additional "painted" samples and/or those that were not frozen. Samples were collected using a random zigzag pattern throughout the area being sampled at a depth of 10 – 12 cm using a stainless-steel cylindrical probe (2.5 cm inside diameter). About 15 soil cores were taken for each sample and placed in a plastic bucket. These were then mixed and transferred into a cloth bag. All items encountering the soil were cleaned and sterilized using heat-sterilization (70ºC) for the cloth bag and Advanced Hand Sanitizer (Germ-X, St. Louis, MO, USA) for the sampler's hands, as well as for the probe and bucket. Care was taken to avoid any contamination with fertilizer dust or other chemical or microbial contaminants. Most samples were stored in the cloth bags in a -80°C freezer until all samples were collected and ready for analysis. The subset of five samples that were not frozen were refrigerated at 1ºC and processed within 2 d of sampling.

Soil Analysis

The soil was analyzed in cooperation with the Brigham Young University—Environmental Analytical Laboratory (BYU—EAL). The analyses completed for this study are found in Table 1-1. Additional chemical analyses were performed and are reported in Table 2-1. Prior to analysis, the samples were thawed and incubated for 14 d in a glasshouse at BYU with 16/8 day/night temperature set points of 25ºC and 15ºC, respectively. The non-frozen samples were also incubated in the same manor. The soil was kept slightly moist as needed to avoid excessive drying, while avoiding leaching of nutrients. The soil was gently mixed for homogeneity and split with an undisturbed portion used for the aggregate stability test and the rest dried and ground for the other biological, physical, and chemical analyses. The selection of the soil health analyses was based on the NRCS Soil Health Technical Note 450-03 (Stott, 2019; Kristen Hicks, personal communication, 2022), which are those officially adopted by the Soil Science Society of America – North American Proficiency Testing Program (www.NAPTprogram.org). Soil health measurements included total organic carbon (TOC), organic matter (OM), permanganate oxidizable organic carbon (POxC), total inorganic carbon (TIC), potentially mineralizable nitrogen (PMN), carbon respiration (CO_2), β-glucosidase (BG), autoclave citrate-extractable (ACE) protein, and aggregate stability (AS).

Statistical Analysis

The soil analysis data was evaluated for differences in chemical, physical, and biological properties by Analysis of Variance (ANOVA) with General Linear Models (GLM) with mean separation via the Tukey-Kramer method (Rstudio software). The sports fields (American football, baseball, softball, soccer, and intermural) were combined for orthogonal comparisons with the other sample types. Additionally, painted versus non-painted, professional versus collegiate, and frozen versus non-frozen comparisons were made. The data was further evaluated by correlating each of the measured variables with each other.

RESULTS

Correlations Among Soil Properties

In general, most soil health indicators evaluated in this study were positively correlated with each other (Fig. 1-2). When summing the Pearson correlation coefficients over all pairwise correlations, PMN had the highest sum and, thus, was used as a basis for comparison across the other soil health measurements with significant, positive correlations: CO_2 respiration (r = 0.81), BG (r = 0.71), TOC (r = 0.62), POxC (r = 0.60), and ACE Protein (r = 0.81). The TC had an equivalent correlation value as TOC but was not included in Fig. 1-2 for simplification. Also note that TIC, silt, and clay contents were weakly correlated as well, with r values of 0.27, 0.33, and 0.32, respectively. In addition to the PMN correlations, other noteworthy correlations ($r \geq$ 0.60) included the ACE protein with TOC (r = 0.60) and BG with CO_2 respiration (r = 0.75) or TOC (r = 0.60).

None of the aggregate stability values were correlated with PMN or soil properties other than texture. The mass of unstable aggregates was negatively correlated with sand (r = -0.64) and positively correlated with silt (r = 0.64) and clay content (r = 0.57). This resulted in the fraction of stable to unstable aggregates having significant, albeit weaker, correlations with sand, silt, and clay contents (*r* = 0.33, -0.33, and -0.29, respectively). Soil texture is known to be a determining factor in soil health values (Nunes et al. 2021), and in general, soil texture impacted soil health values in this study (Fig. 1-3). As sand content increased (and clay and silt decreased) the fraction of stable to unstable aggregates was weakly correlated (*r* = 0.33). Nearly all other soil health metrics decreased significantly with increasing sand (Table 2-4). The mass of unstable aggregates had a strong negative correlation (*r* = -0.64) with TOC (*r* = -0.43), CO_2 respiration (*r* = -0.35), BG (*r* = -0.35), TC (*r* = -0.35), PMN (*r* = -0.34), and POxC (*r* = -0.26).

Management Effects on Soil Properties

There were significant differences among land management categories for individual soil properties, with the exception of the mass of stable aggregates and TIC (Table 1-2). When sports field venues were combined for orthogonal comparisons, the differences were all significant except for TIC (Table 1-2). Not surprisingly, the sand control (sandy soils with no vegetation) had the numerically highest average sand content, although it was only significantly greater than the farm and intermural samples (Tables 1-2 and 1-3). Neither sand nor silt textural classes were significantly different when comparing the sand controls to sports fields, whether evaluated by individual types or collectively (Table 1-3; Supplemental Fig. 1-1). When sports fields were combined, there were no differences in clay textural class between the sand control and sports fields. However, softball, golf, and intermural had significantly higher clay content than the sand control when comparing specific sports (Table 1-3). All of the individual sports were similar in average texture other than intermural sports.

Another physical soil property evaluated in this study is aggregate stability, which is thought to be important in resistance to erosion and water infiltration. There were significant differences for the mass of unstable, stable, and total aggregates (Table 1-2; Supplemental Table 1-2). When comparing individual sport venue types, there was significantly lower total aggregation in football, soccer, and baseball fields than in farm fields; however, there were no significant differences between sports or any other soil (Table 1-3). And there were no differences in stable aggregation. Surprisingly, farm soil had greater unstable aggregation than football, soccer, and baseball fields. When the fraction of unstable to stable aggregates was determined, there was a non-significant trend suggesting farm and urban lawns had lower AS than sports and non-managed forest soils (Table 1-3; Supplemental Table 1-2). The sports field and golf soils had similar AS across venues.

For the soil chemical properties evaluated in this study, significant differences in TOC and PMN were observed (Table 1-2). All of the soils were numerically higher than the sand control and most were significantly higher for individual (Table 1-4) and orthogonal comparisons (Fig. 1-4). (Note that OM values were calculated from TOC and reported in Supplemental Table 1-3.) Although there were trends for golf and forest soils to be higher than other soil, there were no statistical differences for TOC and POxC for any soil type other than the sand control. However, the forest soils had statistically higher TC than football (Table 1-4) and higher for all sport field soils combined, but not for golf (Fig. 1-4i).

The chemical analysis for PMN was similar to the C measurements, with all venues numerically higher than the sand control, although only golf, forest, softball, and soccer were significantly higher (Table 1-4). When combined across sports, all venues were higher than the sand control (Fig. 1-4iv). There were no differences in PMN between any other venues.

For the biological measurements, the sand control was significantly lower than all other venue types for CO_2 respiration and it was significantly lower compared to some venues and numerically the lowest across all venues for BG and ACE protein (Table 1-5). Golf was the only venue statistically higher than the sand control for BG. All venues other than softball, intermural, and farm were higher in ACE Protein compared to the sand control. The orthogonal comparisons were very similar with sport fields lower than forest for ACE protein and lower than golf for BG, but statistically similar to the other venues for ACE protein (Fig. 1-5). When comparing venues other than the sand control, the forest soils were higher in ACE protein than football, softball, and farm soils (Table 1-4). And golf was higher in CO_2 respiration and BG than football and baseball (Table 1-4) as well as higher than all sports field soils combined (Figs. 1-5i and 1-5ii).

Caution should be used when comparing AS results across substantially different soil textural classes (Shedekar 2018). Thus, the data was parsed with a clear separation apparent at 20% clay (Fig. 1-5). Sport and golf samples were combined due to their similar management and construction. Although there were some large numerical differences, there was no statistical significance for between sport/golf and non-sport/golf for the relatively low sand soils with >20% clay content (Fig. 1-5i). However, compared to sport/golf soils the non-sport/golf samples had higher unstable and total aggregates, with a similar trend for stable aggregates for the high sand soils with <20% clay. However, the relative difference for the fraction of stable to unstable aggregates was higher for sport/golf than non-sport/golf.

Texture classifications ranged from sandy to clay loam (Fig. 1-6). For the relatively low sand soils with >20% clay content, all of the soil health measures were numerically higher for sport/golf than non-sport/golf (Fig. 1-5ii). Sport/golf samples with greater than 20% clay content were statistically higher in TOC than sport/golf samples with less than 20% clay content. However, samples containing less than 20% clay were statistically higher in POxC than non-sport samples that contained greater than 20% clay.

Effect of Biological Paint Applied to Sports Fields

There were no statistical differences between painted and non-painted areas ($\alpha < 0.05$; Supplemental Table 1-4). However, the POxC value was nearly double for non-painted compared to painted areas ($\alpha < 0.10$). Interestingly, the other C analyses were all numerically higher for painted areas, although not significantly so.

Effect of Deep Freezing of Soil Samples

Freezing the soils at -80ºC did not negatively impact any of the soil health metrics, with most having numerically higher values and some having statically significant increases (Table 1-6). There was not a difference in TC, but there appeared to be a shift in C fractions with frozen soils having more TOC and less TIC than soils that were processed shortly after sampling without deep freezing. As a result, the fraction of aggregates that were stable were higher in frozen samples. The β-glucosidase values were also significantly higher ($\alpha < 0.10$) for frozen samples. Notably, no differences in biological measurements were found between samples that had undergone the freezing and thawing processes compared with those that did not (Table 1-6). However, significantly higher values of TOC were observed in samples that had been frozen than those that had not been frozen (Table 1-6).

Effect of Level of Sports (Professional vs. Collegiate)

There were several significant differences between professional and collegiate sports fields (Table 1-7). Collegiate fields had higher PMN, TC, and TIC ($\alpha = 0.05$), POxC ($\alpha = 0.10$), and a trend towards higher TOC. The biological properties were also significantly higher in collegiate venues, including CO_2 respiration and ACE protein ($\alpha = 0.05$) and β-glucosidase ($\alpha = 0.10$).

DISCUSSION

Soil Health in Sports Fields

The primary objective of this study was to assess whether sports fields had differing levels of soil health compared to other managed and unmanaged soils. To determine whether soil health is optimum for a specific soil, or a specific function is a complicated process with many connected variables. Based on the biological, chemical, and physical analyses in this study, we found ample evidence that the soil health signatures of sport and golf fields were comparable to and, in some cases, greater than other managed and unmanaged soils. None of the soils were devoid of biological or chemical activity, demonstrating the resilience of sports and golf soils, despite the perception that intensively managed soils are not healthy. Perennial vegetation is known to support soil health (*e.g.*, Li et al. 2021; Veum et al. 2015), and soils with vegetated cover had significantly greater indicators of soil health than the non-vegetated sands (Tables 1-2, 1-4, 1-5; Figs. 1-4, and 1-5). As evidence of this, many of the sports field and golf course soils had high sand content similar to the non-vegetated sand controls (Table 1-3) but had significantly greater chemical and biological soil health values (Tables 1-2, 1-4, 1-5; Figs. 1-4, and 1-5). These results were comparable with soil health values from studies in agricultural systems, including TOC, TC, POxC, PMN, CO_2 respiration, and ACE protein (Nunes et al 2021, Svedin et al 2022, Veum et al 2022).

In order to provide enhanced drainage and resistance to compaction, sports field and golf course soils are often constructed with and/or amended with sand, while minimizing silt and clay content (Wallace et al., 2021), consistent with the soils in our study (Table 1-3). Soil texture and aggregate stability have profound impacts on soil health factors, and soil texture had a significant impact on soil health properties in this study. However, soil texture has been shown to be unaffected by land clearing or urban non-sport land management (Alegre et al. 1986, Pouyat et al. 2007). These findings suggest that managing soil texture for soil health in an urban landscape would likely involve altering the parent material of the soil. This study observed a correlation between soil texture and aggregate stability but showed no difference between managed and unmanaged systems for aggregate stability ratios (percent stable aggregates: percent unstable aggregates). As sand content increased and clay content decreased, the fraction of stable to unstable aggregates increased (Fig. 1-3, Table 2-4). However, most other soil health indicators decreased. Regardless, it is apparent that the intensively managed sports field and golf course soils had soil health results comparable to other types of soils (Tables 1-2, 1-3, 1-4, and 1-5; Figs. 1-4 and 1-5), including farm fields, less intensively managed urban lawns, and non-managed forest soils. The only exception was ACE protein in golf and sports fields, and TC in sports fields.

This study showed that TC, TOC, and OM were not negatively influenced by golf or sports field management practices; however, more studies should be conducted to determine other management practices that are applicable in sport systems to increase these carbon pools. A study by Chahal and Van Eerd (2018) found that TOC increased with the use of cover crops in agricultural systems. Other studies have shown that N fertilization can increase TOC in golf course putting greens without influencing C respiration or PMN (Liu et al. 2011.) Ladha and Chakraborty (2016) also examined the effects of bioavailable N in terms of fertilizer use efficiency on the environment, specifically pollution and climate change, suggesting that steps need to be taken to avoid the complex problems that can result from over-fertilization of N while seeking to maintain plant available N. Future steps for managing PMN in sports field systems may include implementing a variety of turfgrass species and increasing fertilizer use efficiency, but more studies are needed to evaluate the impact of these practices on sport systems.

Additionally, forest, farm, golf, and soccer venues were significantly higher in POxC than the sand control, but farm and urban venues were not significantly different from the sand control, suggesting that farm and urban management practices may have a negative impact on POxC. Studies of POxC in agricultural grain systems found that crop productivity is highly correlated to POxC levels and even identified 415 mg POxC kg^{-1} as a threshold for optimal grain productivity (Svedin et al 2022). Our analysis showed only soccer, softball, farm, golf, and forest venues were above this threshold, although studies are needed in sport systems to determine if this threshold applies to turfgrass, rather than grain cropping systems. Additionally, studies have shown that agricultural management such as crop rotation and heavy tillage have positive and negative effects on soil POxC respectively (Veum et al. 2022). These studies show that the positive and negative effects of land management in soil systems can be translated into sports fields management practices. For the most part, sports fields are maintained as a monoculture, but studies show that crop rotation and low tillage have positive impact on soil PMN and POxC. Furthermore, perennialization (e.g., cool or warm season grasses), has been shown to increase soil health indicators over annual cropping systems in general, regardless of other management, such as tillage or rotational diversity (Li et al. 2021; Veum et al. 2015).

Since all the venues demonstrated greater CO_2 respiration than the sand control, general microbial activity was not negatively impacted by sports fields management practices. Studies have shown that CO_2 respiration is correlated with microbial biomass, making it an important soil health indicator (Franzluebbers et al. 1996, 2016). A study by Dierra et al. (2022) evaluated the effects of turfgrass products on soil health in golf venues and found that Revolution and PlantHelper caused an immediate increase in CO_2 respiration, acting as labile C sources, and Primomaxx and Cutless caused delayed increase in respiration, but none of the products sustained higher levels of respiration over the long term. This suggests that there is potential for soil health to be managed more specifically in sports fields using application products.

Since our forest soils were higher in ACE protein than all other venues except urban soils, management practices likely had an impact on ACE protein. This conclusion is supported by another study that showed negative correlations between land conversion from forest to agriculture and ACE protein, including overall soil health (Benalcazar et al. 2022). While no negative effects of sport field or golf course management on ACE protein or β-glucosidase were found, studies suggest that certain types of management can influence soil health. For example, a study by Liu et al. (2011) found that changes in enzyme activities were positively associated with fertilizer rates in golf greens up to a threshold, after which enzyme activities were negatively affected. Other studies showed that certain products could enhance short-term enzyme activity, but when applied on a long-term basis, did not show a lasting effect (Diera et al. 2020).

The results of this study suggest that the primary management factor impacting microbial respiration is maintaining perennial vegetation. Other management factors, such as intensity of nutrient and pest management, had little to no impact. As soil health is a discipline that is still developing interpretations for multiple soil health indicators across a wide range of land use and land management practices (Hopkins et al. 2023), firm guidelines for soil health interpretation are still lacking. For example, one study suggested that a POxC value of >415 mg kg^{-1} correlated with improved field corn (*Zea mays* L.) yields, but similar studies linking soil health to productivity goals is lacking, and related turfgrass research has not yet been accomplished. However, using the POxC threshold for comparison reveals that the farm, golf, and forest soils were above this threshold and sports fields were not far below (Fig. 1-5).

Soil Health Across Sport Venues

When compared, each of the different sports venue types had similar soil health values, suggesting that differences in management techniques for sports fields had little to no impact (Tables 1-2, 1-3, 1-4, and 1-5; Figs. 1-4 and 1-5). Surprisingly, soil health values for soils that repeatedly received paint were not impacted negatively, with the exception of lower POxC values (Supplemental Table 1-4). Differences were observed between professional and collegiate football venues, with collegiate fields demonstrating higher soil health values. We attribute this to larger budgets resulting in more frequent replacement of professional fields (average of 2.2 for professional vs. 8.7 years for collegiate), and these fields tend to be sandy (Table 1-3). With time, these sandy soils can build organic matter and, thus, microbial activity (Qiu et al. 2014). Thus, the collegiate fields had higher PMN, TC, POxC, CO_2 respiration, ACE protein, and β-glucosidase, as well as a trend towards higher TOC and OM (Tables 1-2 and 1-3; Fig. 1-4). Collegiate fields also had higher TIC, which is likely attributed to age, with deposition of carbonates from irrigation.

Overall, golf soils exhibited higher levels of biological activity than the sports fields, including significantly higher levels of CO_2 respiration and β-glucosidase (Tables 1-2, 1-3, 1-4, and 1-5; Figs. 1-4 and 1-5). Why this trend occurred is not entirely clear, but we speculate, based on experience with many venues, that it may be due to differences in N fertilization. Over fertilization with N results in excessive shoot growth at the expense of root growth (Wallace et al., 2021). Sports fields tend to have relatively high rates of N fertilization because the soils are sandy with low CEC, and thus low nutrient and water holding capacity. They tend to be over irrigated and leach out the N easily. In addition, they tend to have relatively high rates of damage and N is used to help hasten recovery. Although golf soils also tend to have low CEC, they are often less damaged overall and, more importantly, commonly have creeping bentgrass (*Agrostis stolonifera* spp.) on greens and tee boxes in comparison to Kentucky bluegrass (*Poa pratensis* L.) common in sports fields, especially in cool season and transition zones. Bentgrass is particularly sensitive to excess N as it forms thick thatch layers that are very difficult to manage. Thus, golf course managers tend to apply less N than sports field managers (Shaddox et al. 2023). There may be other possible reasons as well.

Correlations Between Soil Health Metrics

Not surprisingly, there were significant correlations among most soil health indicators observed in this study (Fig. 1-2). The exception was aggregate stability, which lacked correlations with any other soil health indicator (Table 2-4). These relationships imply that soil biological and chemical factors have profound impacts on each other and interact in a complex way that sustains plant life in the soil. Increased research on the relationships between soil health indicators and productivity goals would benefit the scientific community and field managers by improving our understanding of the effects of management practices on soil health and providing land managers with actionable, decision-based information.

CONCLUSIONS

The primary objective of this study was to assess soil chemical, biological, and physical health characteristics across various landscapes, including managed sports fields and golf courses, native ecosystems, farm fields, and non-sport urban environments. Soil health values were similar across all soils with actively growing, perennial vegetation, including the intensively managed sports fields. In contrast, the non-vegetated sandy soils had significantly lower soil health values, highlighting that vegetative cover was a more important factor for soil health than management, type of management, type of sport venue, or surface painting. However, soil health in sports fields likely improves with time, as professional venues with relatively more recent construction had lower soil health scores than collegiate fields with greater longevity. Further research is needed to explore the differences in soil health between golf courses and sports fields to develop a better understanding of the impacts of various practices over time. In particular, management practices specific to sport and golf systems (topdressing with sand, overseeding, etc.) should be explored to draw more precise conclusions about the effects of field management on soil health. Further investigations into tailored strategies and their long-term effects will contribute to the continued advancement of soil health management in sports and beyond.

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FIGURES

Figure 1-1. Soil health sampling locations throughout the USA.

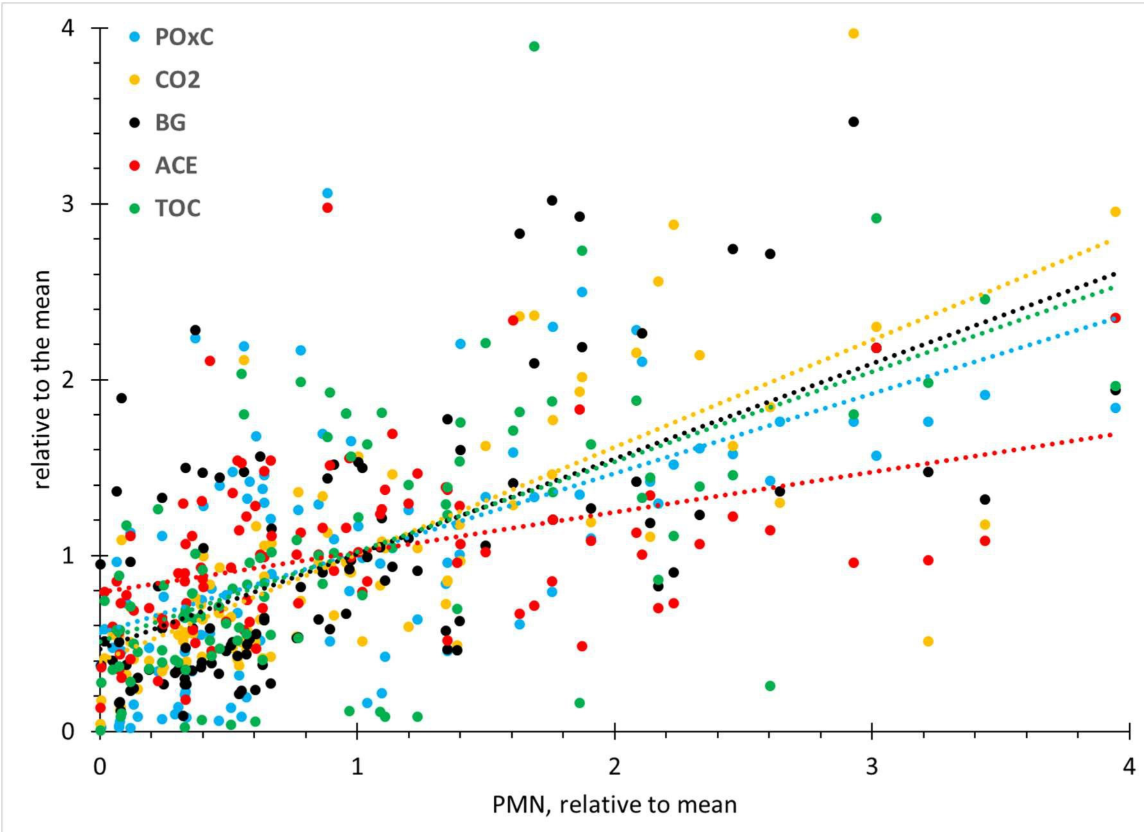


Figure 1-2. Scatter plot showing correlations for soil health tests relative to potentially mineralizable nitrogen. Permanganate oxidizable carbon (x axis), r = 0.60 (POxC, blue points and line), CO_2 respiration, r = 0.81 (CO_2, yellow points and line), β-glucosidase enzyme activity, r = 0.71 (BG, black points and line), autoclave citrate extractable protein, r = 0.81 (ACE, red points and line), and total organic carbon, r = 0.62 (TOC, green points and line) as shown Data for each point was normalized by dividing by the average of all measures in order to graph the data together.

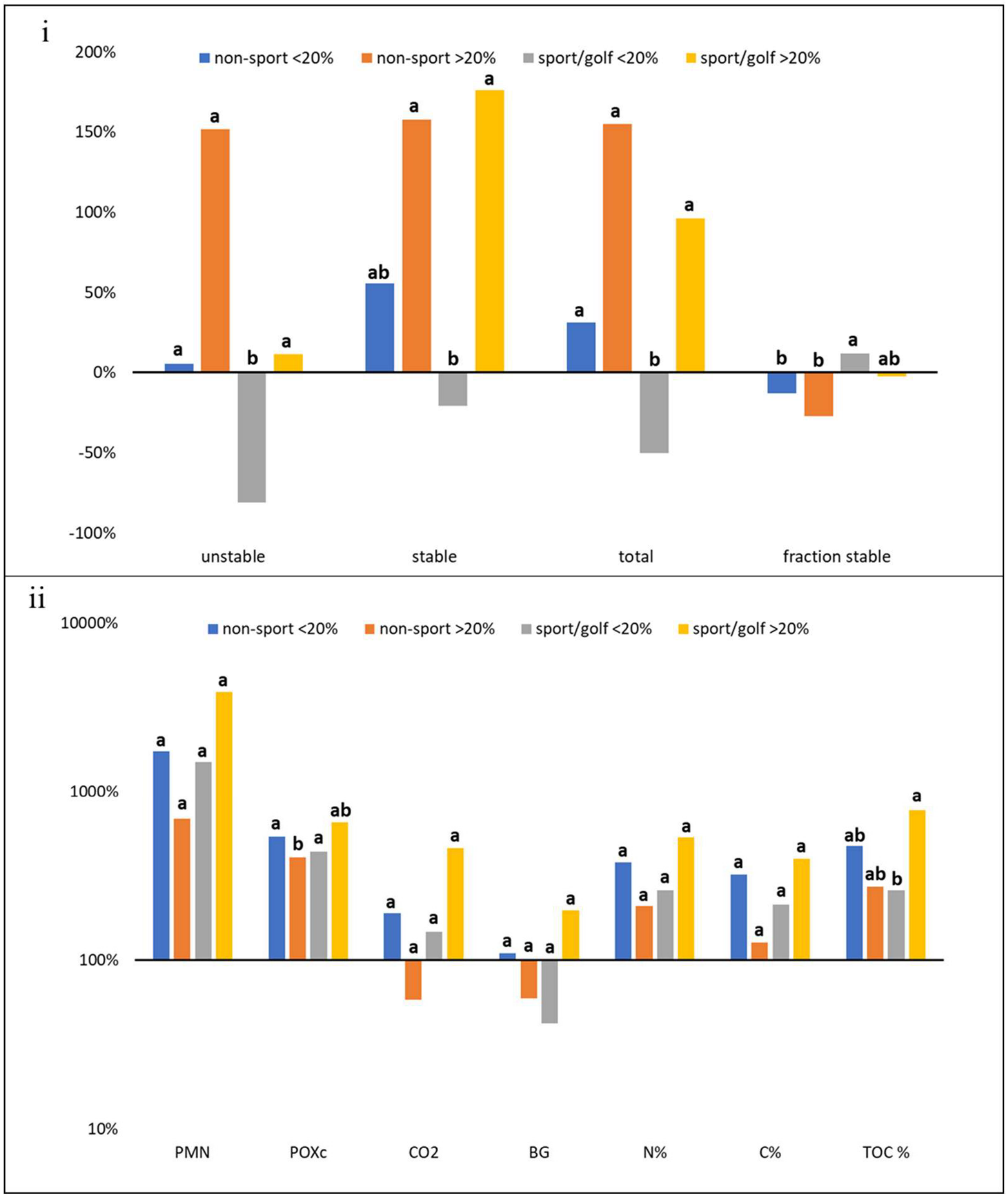


Figure 1-3. Aggregate stability separated into different groups. Total unstable aggregates, total stable aggregates, total aggregates, and fraction stable aggregates are grouped and separated into categories based on their clay content (<20% or >20%) and field type. Values are shown as a percentage relative to the sand control. Statistical differences are designated by lettering.

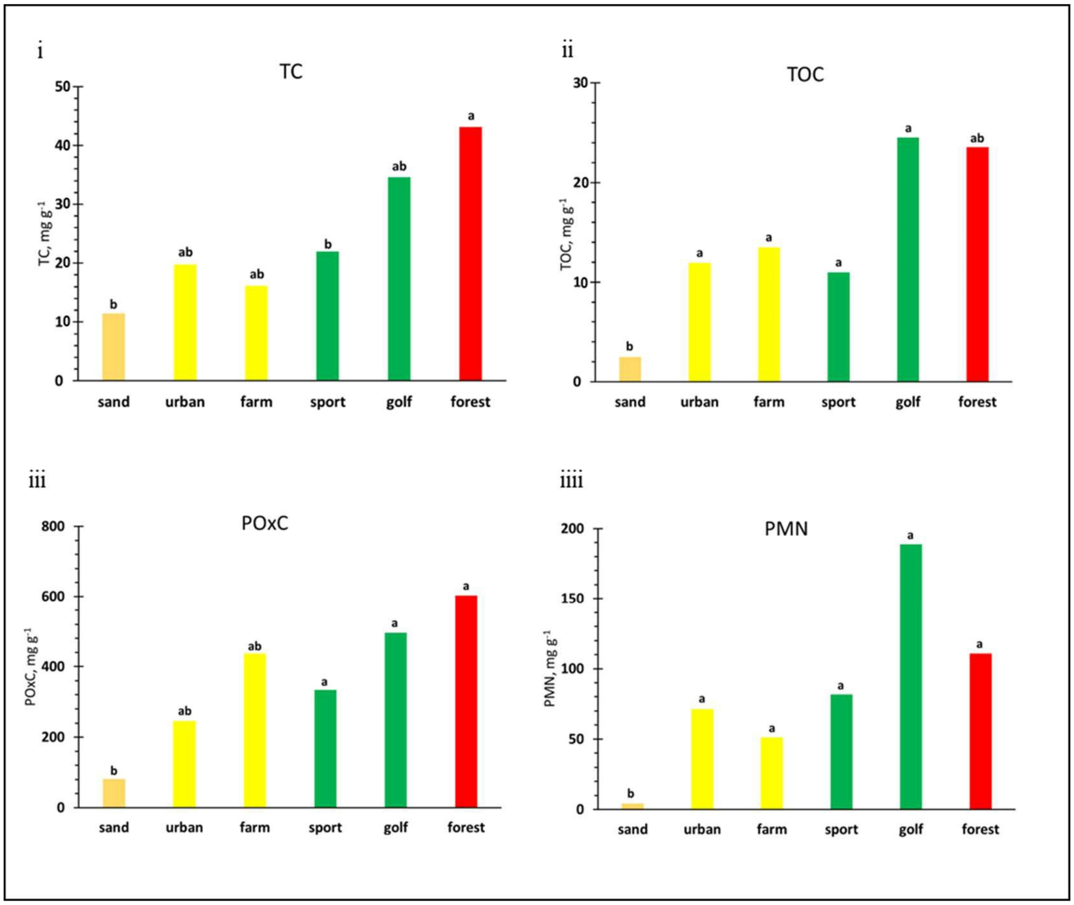


Figure 1-4. Bar graphs of chemical soil health tests for total carbon (TC), total organic carbon (TOC), permanganate oxidizable carbon (POxC), and potentially mineralizable nitrogen (PMN) for sports field and golf course fields (green bars) compared to other managed landscapes (yellow bars), as well as unmanaged vegetated forest soils (red bars) and non-vegetated sandy soils (tan bars). Landscape types with the same lowercase letter are not statistically significantly different at $\alpha = 0.05$.

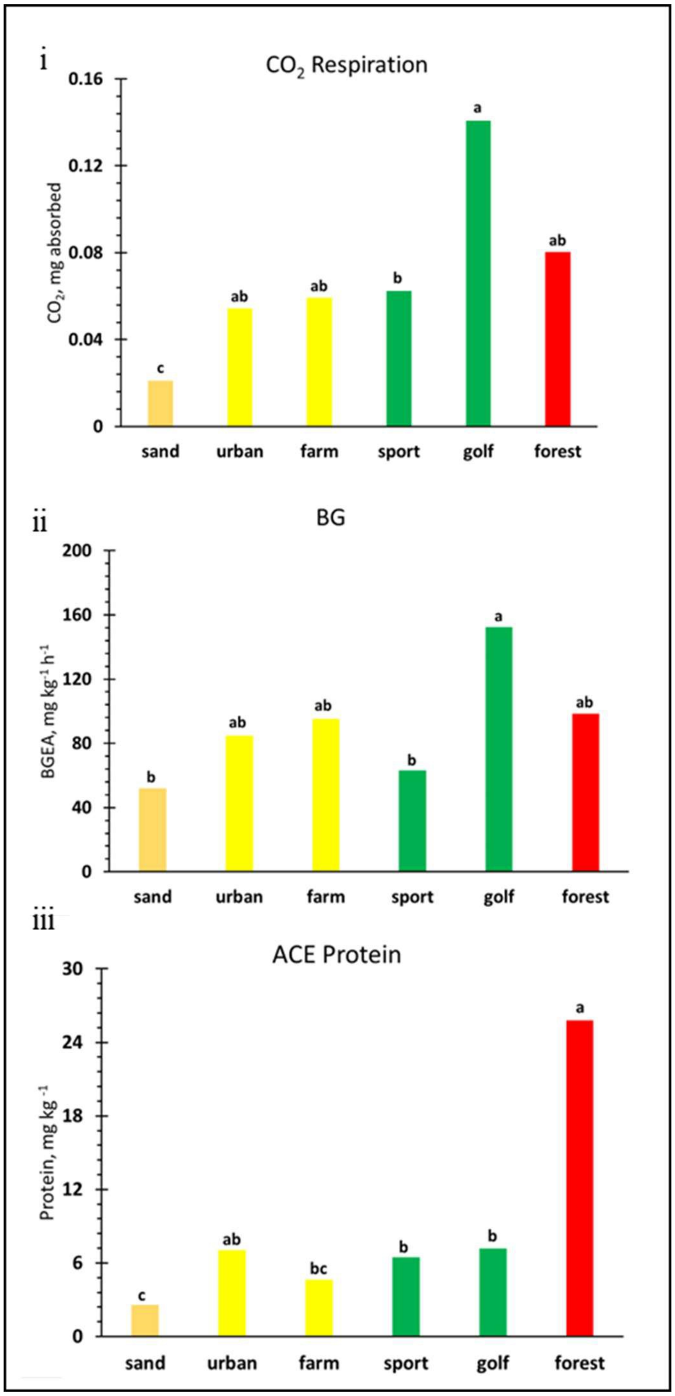


Figure 1-5. Bar graphs of biological soil health tests for microbial respiration (CO_2 Respiration), β-glucosidase (BG) enzyme activity, and autoclave citrate extractable (ACE) protein for sports field and golf course fields (green bars) compared to other managed landscapes (yellow bars), as well as unmanaged vegetated forest soils (red bars) and non-vegetated sandy soils (tan bars). Landscape types with the same lowercase letter are not statistically significantly different at $\alpha = 0.05$.

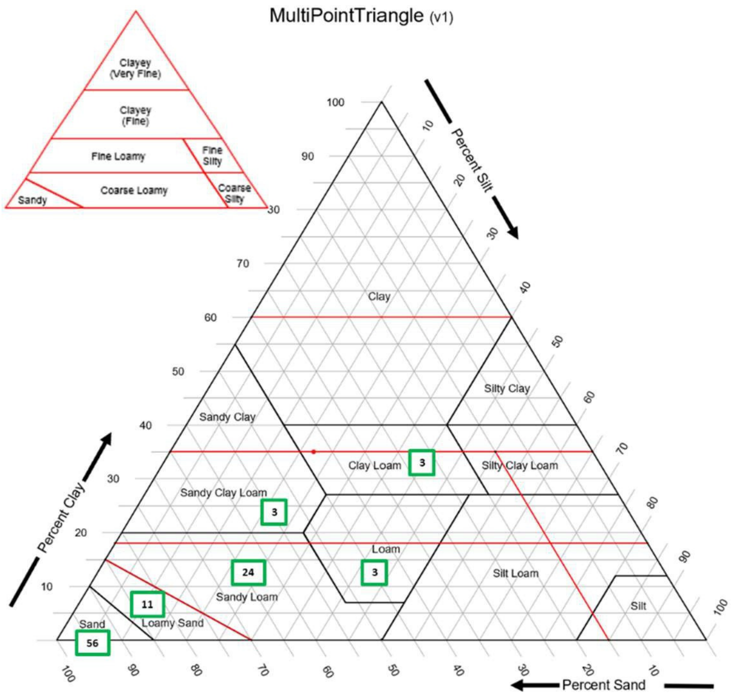


Figure 1-6. Number of soil samples (in green boxes) categorized into each of the textural classes displayed on a multi-point texture triangle.

TABLES

Table 1-1. Methods of analysis.

Physical Properties	
Soil Texture by Hydrometer	Day 1965
Aggregate Stability (AS) by Macroaggregate Wet-Sieve[1]	Stott 2019
Chemical Properties	
Organic Matter (OM) by Combustion	Horneck and Miller 2005
Total Carbon (TC) by combustion[2]	Stott 2019
Total Organic Carbon (TOC) by combustion[2]	Stott 2019
Total Inorganic Carbon (TIC) by combustion[2]	Stott 2019
Permanganate Oxidizable Carbon (POxC)	Stott 2019
Potentially Mineralizable Nitrogen (PMN)[3]	Stott 2019
Biological Properties	
Microbial Activity by 4-day Respiration (CO_2)	Schindelbeck et al. 2016
Enzyme Activity by Beta Glucosidase (BG)	Stott 2019
Autoclave Citrate Extractable (ACE) Protein	Schindelbeck et al. 2016

[1] Wet-sieve apparatus. Eijkelkamp, Wet Sieving Apparatus: Wilmington, NC, USA
[2] CN analyzer. Elementar, VarioELCube, Ronkonkoma, NY, USA
[3] FIAlyzer. FIAlab Instruments, Inc., FIAlyzer1000, Seattle, WA USA

Table 1-2. Statistical significance (*p*-values) comparing individual sports to each other and other landscape types, as well as orthogonal comparisons with all sports combined and compared to other landscape types.

Analyte	Individual Comparisons	Orthogonal Comparisons
Physical Analysis		
Aggregate Stability (AS) - Fraction	0.0267	0.0161
AS - Unstable Aggregates	<0.0001	<0.0001
AS - Stable Aggregates	0.9929	<0.0001
AS - Total Aggregates	0.0003	<0.0001
Texture - Sand	<0.0001	<0.0001
Texture - Silt	<0.0001	<0.0001
Texture - Clay	<0.0001	<0.0001
Chemical Analysis		
Total Carbon (TC)	0.0012	0.0051
Total Inorganic Carbon (TIC)	0.1016	0.1833
Total Organic Carbon (TOC)	0.0011	0.0001
Organic Matter (OM)	<0.0001	<0.0001
Permanganate Oxidizable Carbon (POX-C)	0.0148	0.0089
Potentially Mineralizable Nitrogen (PMN)	<0.0001	<0.0001
Biological Analysis		
Microbial Activity (CO_2)	<0.0001	<0.0001
Enzyme Activity by Beta Glucosidase (BG)	0.0024	0.0052
Autoclave-Citrate Extractable Protein (ACE)	<0.0001	<0.0001

Table 1-3. Soil physical properties of texture and aggregate stability (AS) for sports field and golf course soils compared to non-sport soils, including: farm, urban lawn, forest, and the sand control with no vegetation. Values within a column with the same lowercase letter are not statistically significantly different at α = 0.05.

Venue	Sand	Silt	Clay	AS - Stable	AS - Unstable	AS - Total
	$mg\ g^{-1}$			g		
Sand Control	910 abc	40 bc	50 e	0.68 a	0.64 abc	1.3 ab
Urban Lawn	610 cde	220 ab	170 abc	1.3 a	0.94 ab	2.3 ab
Farm	420 e	350 a	220 a	1.8 a	1.6 a	3.5 a
Forest	670 abcd	190 ab	130 de	0.37 a	0.29 abc	0.66 ab
Intermural	560 de	240 ab	200 ab	1.4 a	0.99 abc	2.4 ab
Football	890 a	50 c	60 de	1.5 a	0.13 c	1.6 b
Soccer	850 ab	70 bc	80 bcde	0.5 a	0.18 bc	0.72 b
Baseball	870 ab	60 c	70 cde	0.6 a	0.14 c	0.72 b
Softball	750 abcd	110 abc	130 abcd	0.7 a	0.22 abc	0.95 ab
Golf	730 bcd	150 abc	130 abcd	1.1 a	0.27 abc	1.4 ab

Table 1-4. Soil chemical properties of Total Organic Carbon (TOC), Total Inorganic Carbon (TIC), Total Carbon (TC), Permanganate-Oxidizable Carbon (POxC), and Potentially Mineralizable Nitrogen (PMN) for sports field and golf course soils compared to non-sport soils, including: farm, urban lawn, forest, and the sand control with no vegetation. Values within a column sharing the same letter(s) are not statistically significantly different at α = 0.05.

Venue	TOC	TIC	TC	POxC	PMN
		$mg\ g^{-1}$		$mg\ kg^{-1}$	
Sand	3 b	9 a	11 b	81 b	4 c
Urban Lawn	12 a	8 a	20 ab	246 ab	71 ab
Farm	13 a	3 a	16 ab	438 ab	51 ab
Forest	24 ab	24 a	43 a	602 a	111 ab
Intermural	14 ab	15 a	29 ab	169 ab	62 ab
Football	10 a	8 a	17 b	288 ab	56 b
Soccer	13 a	16 a	29 ab	416 a	135 a
Baseball	9 a	11 a	19 ab	335 ab	53 ab
Softball	14 a	14 a	29 ab	432 ab	137 ab
Golf	25 a	10 a	35 ab	496 a	189 a

Table 1-5. Soil biological properties of Autoclave Citrate Extractable (ACE) Protein, Enzyme Activity by Beta Glucosidase, and Microbial Activity (CO_2) respiration for various sports field and golf course soils compared to non-sport soils, including: farm, urban lawn, forest, and the sand control with no vegetation. Values within a column sharing the same letter(s) are not statistically significantly different from one another at $\alpha = 0.05$.

Venue	ACE (mg kg $^{-1}$)	BG (mg kg^{-1} h^{-1})	CO_2 (mg)
Sand	2.60 c	0.021 b	51.8 c
Urban Lawn	7.06 ab	0.054 ab	84.8 ab
Farm	4.63 bc	0.059 ab	95.4 ab
Forest	25.78 a	0.080 ab	98.6 ab
Intermural	7.30 abc	0.048 ab	62.0 ab
Football	6.33 b	0.053 b	51.1 b
Soccer	6.75 ab	0.072 ab	83.4 ab
Baseball	7.11 ab	0.049 b	48.4 b
Softball	5.90 bc	0.125 ab	101.6 ab
Golf	7.16 ab	0.141 a	152.5 a

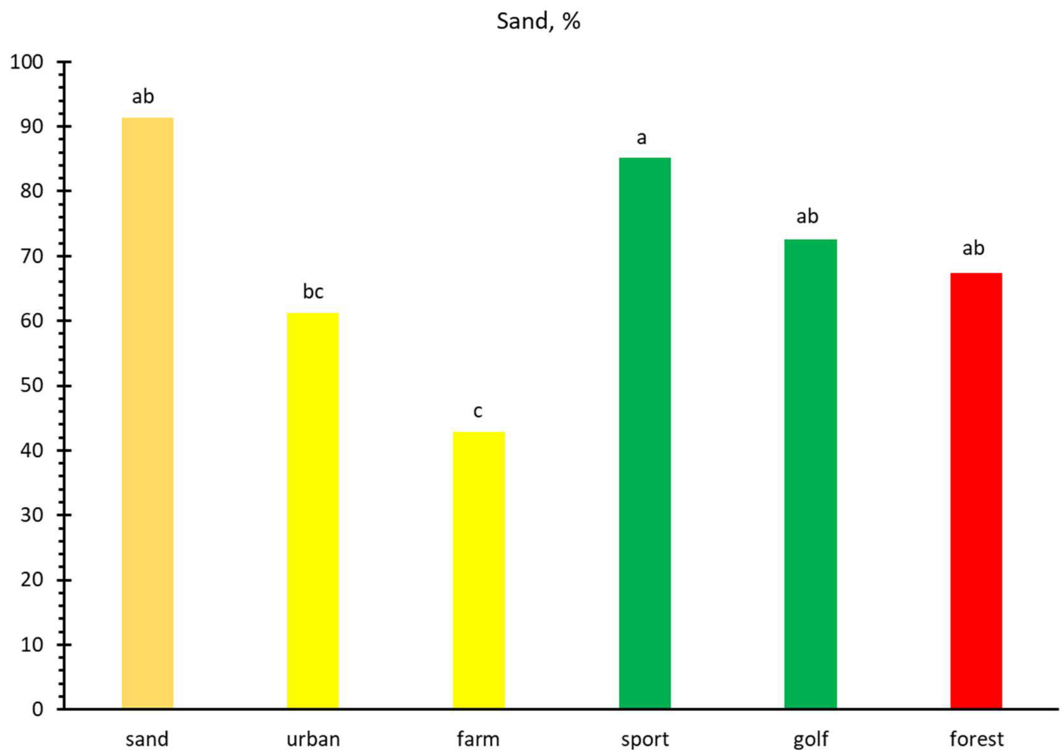
Table 1-6. Average values with corresponding significance values for differences between frozen and non-frozen samples. Shaded values are significantly different.

Variable	Frozen	Non-Frozen	*P*-value
	Physical Analysis		
	|-------------------- g ----------------------|		
Fraction Stable Aggregates	0.87	0.78	*0.0405*
Stable Aggregates	0.11	0.24	*0.7148*
Unstable Aggregates	0.63	0.50	*0.3910*
Total Aggregates	0.739	0.737	*0.9966*
	|------------------- mg g^{-1}---------------------|		
Sand Content	851	831	*0.6716*
Silt Content	74	80	*0.7582*
Clay content	75	89	*0.6398*
	Chemical Analysis		
	|-------------------mg g^{-1}---------------------|		
Total Organic Carbon (TOC)	2114	1311	*0.0057*
Total Inorganic Carbon (TIC)	937	1861	*0.0927*
Total Carbon (TC)	3052	3172	*0.8101*
Organic Matter (OM)	3.6	2.3	*0.0038*
Permanganate Oxidizable Carbon (POx-C)	706.0	590.0	*0.1131*
Potentially Mineralizable Nitrogen (PMN)	193.0	162.0	*0.6962*
	Biological Analysis		
Reactive Carbon (Respiration), mg g^{-1}	0.130	0.144	*0.4452*
Enzyme activity - Beta Glucosidase (mg PNP kg^{-1})	139.0	74.8	*0.0761*
Autoclave-Citrate Extractable Protein, mg g^{-1}	6.82	6.38	*0.4780*

Table 1-7. Average values for professional vs collegiate comparisons. Shaded values are significantly different at α = 0.05.

Variable	Professional	Collegiate	*P*-value
	Physical analysis		
	|----------------------mg g^{-1}	-----------------------|	
Fraction Stable Aggregates	0.85	0.83	*0.6375*
Stable Aggregates	0.48	1.16	*0.4610*
Unstable Aggregates	0.14	0.13	*0.9695*
Total Aggregates	0.62	1.29	*0.4635*
	|---------------------- mg g^{-1}	-----------------|	
Sand Content	884	848	*0.4667*
Silt Content	48	73	*0.2030*
Clay content	68	79	*0.3382*
	Chemical Analysis		
	|----------------------mg g^{-1}	-----------------------|	
Total Organic Carbon (TOC)	1039	1241	*0.1884*
Total Inorganic Carbon (TIC)	652	1275	*0.0363*
Total Carbon (TC)	1691	2496	*0.0307*
Organic Matter (OM)	1787	2134	*0.1884*
Permanganate Oxidizable Carbon (POX-C)	271.0	380.0	*0.0975*
Potentially Mineralizable Nitrogen	57.4	108.0	*0.0401*
	Biological Analysis		
Reactive Carbon (Respiration), mg g^{-1}	0.054	0.076	*0.0307*
Enzyme activity - Beta Glucosidase (mg PNP kg^{-1})	60.5	74.7	*0.0636*
Autoclave-Citrate Extractable Protein, mg g^{-1}	5.87	6.90	*0.0244*
Organic Matter (OM), %	1787	2134	*0.1884*

SUPPLEMENTARY MATERIALS



Supplemental Figure 1-1. Bar charts of percent sand content by venue type. Sports field and golf course, other managed landscapes (yellow bars) are compared with non-vegetated sandy soils and unmanaged vegetated forest soils. Landscape types sharing the same letter(s) are not statistically significantly different at $\alpha = 0.05$

Supplemental Table 1-1a. Soil sampling dates and locations for American football. Venues marked with an "*" indicate samples that were not frozen or stored before drying and grinding.

	Date	Venue	Nearest City	Coordinates	Level
		AMERICAN FOOTBALL			
1	9/23/2021	Baltimore Ravens - M&T Bank Stadium	Baltimore, MD	39.277893, -76.622696	professional
2	10/11/2021	Chicago Bears - Soldier Field	Chicago, IL	41.860615, -87.617338	professional
3	9/30/2021	Green Bay Packers - Ray Nitschke Field	Green Bay, WI	44.497679, -88.056608	professional
4	1/14/2022	Jacksonville Jaguars - TIAA Bank Field	Jacksonville, FL	30.323677, -81.637332	professional
5	10/19/2021	Philadelphia Eagles - Lincoln Financial Field	Philadelphia, PA	39.901108, -75.167477	professional
6	10/19/2021	Philadelphia Eagles - Nova Care Complex Practice Facility	Philadelphia, PA	39.906959, -75.176271	professional
7	10/15/2021	Pittsburg Steelers - Heinz Field	Pittsburg, PA	40.445688, -80.015482	professional
8	10/15/2021	Pittsburg Steelers - Heinz Field (painted)	Pittsburg, PA	40.445688, -80.015482	professional
9	9/1/2021	Brigham Young University - football practice field	Provo, UT	40.257905, -111.655807	collegiate
10	3/24/2022	Brigham Young University - LaVell Edwards Stadium spring	Provo, UT	40.257254, -111.655804	collegiate
11	9/1/2021	Brigham Young University - LaVell Edwards Stadium fall	Provo, UT	40.257254, -111.655804	collegiate
12	3/24/2022	Brigham Young University - LaVell Edwards Stadium (painted)	Provo, UT	40.257254, -111.655804	collegiate
13	7/6/2022	Brigham Young University – football practice field*	Provo, UT	40.257905, -111.655807	collegiate
14	7/6/2022	Brigham Young University – LaVell Edwards Stadium*	Provo, UT	40.257254, -111.655804	collegiate
15	10/27/2021	Clemson University - Memorial Stadium - new sod	Clemson, SC	34.678727, -82.843088	collegiate
16	10/27/2021	Clemson University - Memorial Stadium - old sod	Clemson, SC	34.678727, -82.843088	collegiate
17	9/10/2021	Colorado University - Folsom Field	Denver, CO	40.009369, -105.267135	collegiate
18	10/12/2021	Michigan State University - Spartan Stadium	East Lansing, MI	42.728037, -84.484943	collegiate
19	10/12/2021	Michigan State University - Spartan Stadium (painted)	East Lansing, MI	42.728037, -84.484943	collegiate
20	10/18/2021	Penn State University - Beaver Stadium	State College, PA	40.812166, -77.856082	collegiate
21	10/18/2021	Penn State University - Beaver Stadium (painted)	State College, PA	40.812166, -77.856082	collegiate
22	12/16/2021	Texas A&M University - Kyle Field	Bryan, TX	30.609863, -96.340246	collegiate
23	12/16/2021	Texas Christian University - Carter Stadium	Fort Worth, TX	32.709510, -97.367807	collegiate
24	12/16/2021	Texas Christian University - Carter Stadium (painted-purple)	Fort Worth, TX	32.709510, -97.367807	collegiate
25	12/16/2021	Texas Christian University - Carter Stadium (painted-white)	Fort Worth, TX	32.709510, -97.367807	collegiate
26	12/16/2021	Texas Christian University - football practice field	Fort Worth, TX	32.707818, -97.367306	collegiate
27	12/17/2021	University of Houston - west football practice	Houston, TX	29.725357, -95.349768	collegiate
28	12/17/2021	University of Houston - east football practice	Houston, TX	29.725292, -95.349199	collegiate
29	1/13/2022	University of Miami - football practice field	Miami, FL	25.713548, -80.281378	collegiate

Supplemental Table 1-1a (continued). Soil sampling dates and locations. Venues marked with an "*" indicate samples that were not frozen or stored before drying and grinding.

	Date	Venue	Nearest City	Coordinates	Level
		AMERICAN FOOTBALL (continued)			
30	10/29/2021	University of Virginia - Scott Stadium	Charlottesville, VA	38.031147, - 78.513769	collegiate
31	9/30/2021	University of Wisconsin - Camp Randall Stadium	Madison, WI	43.070084, - 89.412723	collegiate
32	10/1/2021	Utah State University - football practice field	Logan, UT	41.754588, - 111.809046	collegiate
33	10/4/2021	Virginia Military Institute - Foster Stadium	Lexington, VA	37.788050, - 79.433880	collegiate
34	10/4/2021	Virginia Military Institute - Foster Stadium (painted)	Lexington, VA	37.788050, - 79.433880	collegiate
35	10/29/2021	Virginia Tech University - Lane Stadium	Blacksburg, VA	37.219892, - 80.418159	collegiate
36	10/29/2021	Virginia Tech University - Lane Stadium (painted)	Blacksburg, VA	37.219892, - 80.418159	collegiate
37	12/18/2021	Huntington High Raiders - football practice field	Shreveport, LA	32.448839, - 93.854963	K-12

Supplemental Table 1-1b. Soil sampling dates and locations for baseball, softball, and intermural. Venues marked with an "*" indicate samples that were not frozen or stored before drying and grinding.

	Date	Venue	Nearest City	Coordinates	Level
		BASEBALL			
38	10/20/2021	Baltimore Orioles - Camden Yards	Baltimore, MD	39.283662, -76.621647	professional
39	9/29/2021	Minnesota Twins - Target Field outfield	Minneapolis, MN	44.981704, -93.277526	professional
40	9/29/2021	Minnesota Twins - Target Field infield	Minneapolis, MN	44.981704, -93.277526	professional
41	10/19/2021	Philadelphia Phillies - Citizen Bank Park	Philadelphia, PA	39.904826, -75.165845	professional
42	3/18/2022	Seattle Mariners - T-Mobile Park	Seattle, WA	47.591253, -122.332443	professional
43	11/11/2021	St. Louis Cardinals - Busch Stadium existing soil under new sod	St. Louis, MO	38.621642, -90.192179	professional
44	11/11/2021	St. Louis Cardinals - Busch Stadium new sod	St. Louis, MO	38.621642, -90.192179	professional
45	10/18/2021	Penn State University - Medlar Field	State College, PA	40.812251, -77.852439	collegiate
46	12/16/2021	Texas A&M University - Blue Bell Park	Bryan, TX	30.605986, -96.341452	collegiate
47	12/16/2021	Texas Christian University - Lupton Stadium	Fort Worth, TX	32.702700, -97.372062	collegiate
48	1/14/2022	University North Florida - Harmon Stadium	Jacksonville, FL	30.275099, -81.508484	collegiate
49	1/13/2022	University of Miami - Alex Rodriguez Park	Miami, FL	25.712030, -80.282297	collegiate
50	9/3/2021	University of Nevada Las Vegas - Earl Wilson Stadium	Las Vegas, NV	36.111456, -115.147713	collegiate
51	10/4/2021	Virginia Military Institute - Gray Minor Stadium	Lexington, VA	37.792525, -79.440085	collegiate
		SOFTBALL			
52	3/24/2022	Brigham Young University - Larry H. Miller Park	Provo, UT	40.254874, -111.652009	collegiate
53	7/6/2022	Brigham Young University - Larry H. Miller Park*	Provo, UT	40.254874, -111.652009	collegiate
54	12/17/2021	University of Houston - Cougar Softball Stadium	Houston, TX	29.727064, -95.349066	collegiate
55	9/30/2021	University of Wisconsin - Goodman Softball Complex	Madison, WI	43.081263, -89.429589	collegiate
56	10/29/2021	Virginia Tech University - Tech Softball Park	Blacksburg, VA	37.218747, -80.420039	collegiate
57	2/4/2022	Southwest High School Eagles	El Centro, CA	32.774552, -115.580282	K-12
		INTERMURALS			
58	12/10/2021	Arrington Middle School	Birmingham, AL	33.473166, -86.870427	K-12
59	12/1/2021	Mariposa Basin Park	Albuquerque, NM	35.155366, -106.694834	K-12
60	12/17/2021	Santa Clara Little League Park	Santa Clara, UT	37.133029, -113.639253	K-12
61	10/12/2021	Michigan State University - intermural fields	East Lansing, MI	42.723884, -84.468278	collegiate
62	2/4/2022	Saguaro Park Playground - City of Yuma	Yuma, AZ	32.652794, -114.498872	K-12

Supplemental Table 1-1c. Soil sampling dates and locations for soccer. Venues marked with an “*” indicate samples that were not frozen or stored before drying and grinding.

	Date	Venue	Nearest City	Coordinates	Level
		SOCCER (INTERNATIONALLY KNOWN AS FOOTBALL)			
63	10/11/2021	Chicago Fire - SeatGeek Stadium	Chicago, IL	41.764861, -87.806683	professional
64	10/11/2021	Chicago Fire - soccer practice field	Chicago, IL	41.786574, -87.731391	professional
65	9/9/2021	Colorado Rapids - Dick's Sporting Goods Park	Denver, CO	39.805439, -104.891731	professional
66	12/16/2021	FC Dallas - Toyota Stadium	Frisco, TX	33.154316, -96.835560	professional
67	10/30/2021	Salt Lake REAL - Rio Tinto Stadium	Salt Lake City, UT	40.583374, -111.893359	professional
68	9/1/2021	Brigham Young University - Haws Field	Provo, UT	40.247088, -111.657912	collegiate
69	7/6/2022	Brigham Young University - Haws Field*	Provo, UT	40.247088, -111.657912	collegiate
70	9/1/2021	Brigham Young University - South Field	Provo, UT	40.246732, -111.655546	collegiate
71	7/6/2022	Brigham Young University - South Field*	Provo, UT	40.246732, -111.655546	collegiate
72	9/7/2021	Colorado State University soccer field	Fort Collins, CO	40.569831, -105.088285	collegiate
73	3/18/2022	Seattle University - Championship Field	Seattle, WA	47.607086, -122.314950	collegiate
74	12/16/2021	Texas A&M University - Ellis Field	Bryan, TX	30.603867, -96.344340	collegiate
75	12/16/2021	Texas Christian University - Garvey-Rosenthal Stadium	Fort Worth, TX	32.702629, -97.368443	collegiate
76	9/3/2021	University Nevada Las Vegas - women's soccer practice	Las Vegas, NV	36.112498, -115.148378	collegiate
77	9/3/2021	University Nevada Las Vegas Johann Stadium	Las Vegas, NV	36.112577, -115.146875	collegiate
78	12/17/2021	University of Houston - Corbin J. Robertson Stadium	Houston, TX	29.721789, -95.348998	collegiate
79	1/13/2022	University of Miami - Cobb Stadium	Miami, FL	25.713482, -80.282674	collegiate
80	9/30/2021	University of Wisconsin - McClimon Soccer Complex	Madison, WI	43.077955, -89.426141	collegiate
81	10/1/2021	Utah State University - Chuck & Gloria Bell Field	Logan, UT	41.756398, -111.808435	collegiate
82	10/29/2021	Virginia Tech University - Thompson Field	Blacksburg, VA	37.219961, -80.421915	collegiate
83	10/23/2021	Washington State University - lower soccer field	Spokane, WA	46.730125, -117.156409	collegiate

Supplemental Table 1-1d. Soil sampling dates and locations for golf. Venues marked with an "*" indicate samples that were not frozen or stored before drying and grinding.

	Date	Venue	Nearest City	Coordinates	Level
		GOLF			
84	9/20/2021	Caribou Highlands Golf Course - fairways	Grace, ID	42.608431, -111.789926	professional
85	9/20/2021	Caribou Highlands Golf Course - greens	Grace, ID	42.608431, -111.789926	professional
86	1/17/2022	The Club at Savannah Harbor	Savannah, GA	32.088545, -81.082667	professional
87	2/8/2022	Torrey Pines Golf Course	La Jolla, CA	32.905917, -117.246391	professional
88	3/24/2022	Brigham Young University - golf green	Provo, UT	40.246014, -111.655945	collegiate
89	10/27/2021	Clemson University - John E. Walker Sr Course – green #8	Clemson, SC	34.664386, -82.842091	collegiate
90	10/27/2021	Clemson University - John E. Walker Sr Course – fairway #7	Clemson, SC	34.664386, -82.842091	collegiate
91	10/23/2021	Washington State University - Palouse Ridge Club - fairways	Spokane, WA	46.738461, -117.140237	collegiate
92	10/23/2021	Washington State University - Palouse Ridge Club - greens	Spokane, WA	46.738468, -117.138022	collegiate

Supplemental Table 1-1e. Soil sampling dates and locations for non-sport/golf locations (controls). Venues marked with an "*" indicate samples that were not frozen or stored before drying and grinding.

	Date	Venue	Nearest City	Coordinates
		FARM		
93	12/10/2021	anonymous	Kearney, NE	40.637307, -99.127471
94	2/4/2022	anonymous	El Centro, CA	32.797731, -115.582367
95	10/13/2021	anonymous	Danville, MI	42.6633121, -84.283167
96	9/20/2021	Christensen BKR Farms	Grace, ID	42.614162, -111.796781
		FOREST		
97	12/15/2021	Bangor City Forest	Bangor, ME	44.862717, -68.741058
98	3/18/2022	Bullitt Fireplace Trail in Squak Mountain State Park	Issaquah, WA	47.510067, -122.051304
99	10/16/2021	City of Coraopolis	Coraopolis, PA	40.458170, -80.193011
100	10/13/2021	Fleming Creek at Parker Mill County Park	Ann Arbor, MI	42.273912, -83.668089
101	12/17/2021	Lanana Creek Trail	Nacogdoches, TX	31.610382, -94.642140
		SAND WITH NO PLANTS		
102	2/4/2022	Juan Bautista Historical Trail	San Juan Bautista, CA	36.831670, -121.533717
103	2/8/2022	Torrey Pines Golf Course sand bunker	La Jolla, CA	32.902438, -117.249221
104	2/8/2022	Torrey Pines State Reserve South Beach	La Jolla, CA	32.928961, -117.258442
105	10/23/2021	Washington State University - Palouse Ridge Golf Club sand bunker	Spokane, WA	46.737985, -117.134583
		URBAN LAWN GRASS		
106	9/23/2021	Baltimore Ravens - M&T Bank Stadium	Baltimore, MD	39.279355, -76.623065
107	9/9/2021	Colorado Rapids - Dick's Sporting Goods Park	Denver, CO	39.805439, -104.891731
108	12/3/2021	David Allen yard	Fargo, ND	46.815532, -96.887843
109	10/21/2021	Phil and Carolyn Wygans yard	Hampton, VA	37.065080, -76.346741
110	12/20/2021	White Rock Cemetery	Nacogdoches, TX	31.67750, -94.35572

Supplemental Table 1-2. Soil physical property aggregate stability (AS) for sports field and golf course soils compared to non-sport soils, including: farm, urban lawn, forest, and the sand control with no vegetation. Values within a column sharing the same letter(s) are not statistically different from one another.

Venue	AS - Stable	AS - Unstable	AS - Total	Fraction Stable:Unstable
	---------------------------- g	-------------------------------		
Sand Control	0.68 ab	0.64 ab	1.3 ab	0.70 a
Urban Lawn	1.3 ab	0.94 a	2.3 a	0.58 a
Farm	1.8 a	1.6 a	3.4 a	0.56 a
Forest	0.37 ab	0.28 ab	0.66 ab	0.79 a
Sport	1.0 b	0.19 b	1.2 b	0.82 a
Golf	1.1 ab	0.27 ab	1.4 ab	0.82 a

Supplemental Table 1-3. Soil properties of Total Inorganic Carbon (TIC) and Organic Matter (OM) for sports field and golf course soils compared to non-sport soils, including: farm, urban lawn, forest, and the sand control with no vegetation. Values within a column sharing the same letter(s) are not statistically different from one another.

Venue	TIC	OM
Sand Control	0.90 a	0.43 c
Urban Lawn	0.78 a	2.1 abc
Farm	0.26 a	2.3 abc
Forest	2.4 a	4.0 ab
Intermural	1.5 a	2.4 abc
Football	0.75 a	1.7 bc
Soccer	1.6 a	2.2 abc
Baseball	1.1 a	1.5 abc
Softball	1.6 a	2.5 abc
Golf	1.0 a	4.2 a

Supplemental Table 1-4. Average values for painted vs non-painted comparisons. Shaded values are statistically significant.

Variable	Painted	Non-painted	*P*-value
	Physical analysis		
	|-----------------------mg g^{-1}	-----------------------|	
Fraction Stable Aggregates	0.89	0.87	*0.7650*
Stable Aggregates	4.92	0.60	*0.3632*
Unstable Aggregates	0.10	0.07	*0.4456*
Total Aggregates	5.03	0.67	*0.3589*
	|--------------------- mg g^{-1}	-----------------|	
Sand Content	879	852	*0.5886*
Silt Content	48	66	*0.5886*
Clay content	73	82	*0.6937*
	Chemical Analysis		
	|-----------------------mg g^{-1}	-----------------------|	
Total Organic Carbon (TOC)	1112	1001	*0.3702*
Total Inorganic Carbon (TIC)	1611	1448	*0.7062*
Total Carbon (TC)	499	446	*0.8162*
Organic Matter (OM)	1.9	1.7	*0.7687*
Permanganate Oxidizable Carbon (POX-C)	138.0	262.0	*0.0753*
Potentially Mineralizable Nitrogen	55.4	68.5	*0.3379*
	Biological Analysis		
Reactive Carbon (Respiration), mg g^{-1}	0.045	0.057	*0.3296*
Enzyme activity - Beta Glucosidase (mg PNP kg^{-1})	45.3	40.5	*0.9120*
Autoclave-Citrate Extractable Protein, mg g^{-1}	6.10	7.19	*0.1645*

CHAPTER 2

Soil Fertility Correlations using American Sports Fields

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ABSTRACT

There is speculation that intensive use of fertilizers harms soil health. Sports fields are among the most intensively managed soils, especially regarding fertilizer application. The objectives of this study were to compare these sports fields with other managed and non-managed soils regarding fertility; and to examine the correlations between these and soil health parameters. Soil samples (n = 110) were collected from a diverse range of sports fields and, for comparative purposes, golf courses, farm fields, non-sport urban, undisturbed forest, and non-vegetated sand soils. All vegetated soils had numerically higher nutrient concentrations than the non-vegetated sands. The fertilized venues were generally higher for the less mobile nutrients with poor solubility (P, Zn, Fe, Mn, Cu) and lower in pH than the sand control. Somewhat surprisingly, the non-fertilized forest was generally equivalent to the fertilized venues in nutrients. The K, Mg, Zn, Mn, Cu, and Fe averages in sports fields were 429, 728, 22, 50, 3.6, and 154 mg kg^{-1}, respectively. This was similar to other soils having turfgrass or other vegetation, with averages of 648, 409, 18, 116, 3.6, and 127 mg kg^{-1}, respectively. However, these were all statistically higher than soils with no vegetation, with averages of 134, 124, 1.8, 15, 0.39, and 33, respectively**.** In general, nutrient concentrations and EC were positively correlated, but tended to decline with increasing sand content. Sports fields had ample soil fertility and reasonable pH and EC, although they had excessively high soil P concentrations.

INTRODUCTION

It has long been recognized that the "fertility" of the soil is vital to maintaining a healthy ecosystem (Hopkins 2020). Degradation of soil has led to reduced crop production and even led to the demise of some civilizations (Hillel et al. 1992). For example, early colonial settlers in the USA initially enjoyed the bounty of nutrient rich soils but yields and crop health declined steadily after many years of mining nutrients from the soil through crop harvest. Eventually, the importance of building up the fertility of the soil and maintaining it with fertilizers was realized, which was an important part of the dramatic increases in crop yields as a result of the Green Revolution (Hopkins and Hansen, 2019).

However, it is easy to assume that the adage of "if some is good, then more is better" is true. But this is not the case with fertilizer. As with humans, once the optimum amount of nutrients is taken up by plants there is no further advantage of additional uptake. And, in fact, excessive nutrients can be detrimental. High concentrations of nutrients can be directly toxic. This is especially true for nutrients, such as copper (Cu) and boron (B), that have a narrow range of sufficiency (Hopkins 2020). In other cases, an excess can negatively impact desired growth, especially with nitrogen (N) (Geary et al. 2014). And, excessive concentrations of nutrients can inhibit the availability of other nutrients, such as phosphorus (P) induced micronutrient deficiencies (Barben et al.2011; Hopkins 2015). In addition to negative impacts on plants, nutrient excess can be harmful to the environment (Hopkins 2020). For example, improperly managed N is known to degrade air quality and excess N and P degrade water quality (LeMonte et al. 2016, 2018; Ransom et al. 2020). Finally, excessive fertilization is wasteful of the natural resources (mined ores, fossil fuels, etc.) used in their production and transportation.

Although fertilizers are important, these are increasingly scrutinized by many concerned landowners, managers, and scientists (Hobbs et al. 2008). The idea that fertilizer use is detrimental for soil health is a popular speculation (Harmel and Haney 2013). Golf and sports turf are arguably the most intensively managed soil systems in the world, including with fertilization (Gillette et al. 2016, Liu et al 2011, Streeter and Schilling 2018). In these venues, it is common to apply fertilizer multiple times per year. For example, some managers apply N fertilizer at very small doses every 1-4 weeks to "spoon-feed" the grass. Maintaining soil fertility is as essential as it is for crop growth, although the reasoning is more for safe and functional playing surfaces, as well as for aesthetics. Nutrient deficiencies cause an array of problems from stunted growth to plant death. Additionally, in sport and golf systems, nutrient problems can increase growth of undesired turfgrass species [e.g., annual bluegrass (*Poa annua*)] and can result in increased pesticide usage when opportunistic pests and pathogens become a problem.

Chemical properties of soil are important indicators of soil fertility, which are critical for overall soil health. Historically, land managers have used traditional soil analyses, which largely assess chemical properties, to quantify "soil fertility" based on the availability of essential plant nutrients (Bavougian et al. 2019). Nutrient extraction and analyses are important for understanding what chemical nutrients are present in the soil and their bioavailability to maintain the soil in a condition of adequate, but not excessive nutrient status.

The objectives of this study are to evaluate a geographically diverse set of sports fields for comparison with golf courses, urban landscapes, farm fields, and native systems to: (1) measure soil properties related to soil chemistry, including: pH, salinity as electrical conductivity (EC), phosphorous (P), potassium (K), sulfate-sulfur (SO_4 -S), calcium (Ca), magnesium (Mg), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and boron (B), (2) determine if there are significant differences among these analyses between sport/golf venues and non-sport/golf soils; and (3) correlate the chemical soil properties to each other, as well as with the soil health parameters reported in Chapter 1. Additional objectives were to similarly evaluate subsets of the sports fields in painted verses non-painted grass areas, collegiate verses professional level sports, and storage conditions of soil prior to analysis (frozen verses nonfrozen).

MATERIALS AND METHODS

Sampling

Soil samples (n = 110, see Supplemental Table 1-1 and Fig. 1-1) were collected between September 2021 and April 2022 from various sports fields, as well as golf courses, farm fields, non-sport urban, non-plant sand soils (beaches and golf sand traps), and undisturbed native soils (forests, and deserts). The sports field samples represent a diversity of geographical sites and facility types (municipal, K-12, collegiate, and professional). These represent American football, American soccer (internationally known as "football"), baseball, softball, and multi-sport intermural fields. These soils were typically sandy (Supplemental Fig. 1-1), which is common for constructed sports fields, as well as for golf courses. In eight American football fields, an additional soil sample was taken from areas where team logos had been painted on the turfgrass multiple times each season. Additionally, in five American sports fields, an additional soil sample was taken, just prior to performing the analyses, that would not be stored in a freezer with the rest of the samples. This was done to ascertain the difference between frozen and non-frozen analysis results to verify that freezing did not catastrophically impact test results.

One sample was taken per field, except for fields that had additional "painted" samples and those that were not frozen. Samples were collected using a random zigzag pattern throughout the area being sampled at a depth of 10 – 12 cm using a stainless-steel cylindrical probe. About

15 soil cores were taken for each sample and placed in a plastic bucket. These were then mixed and transferred into a cloth bag. All items coming into contact with the soil were cleaned and sterilized using Advanced Hand Sanitizer (Germ-X, St. Louis MO) for the sampler's hands and the probe and bucket and heat-sterilization (70ºC) for the cloth bag. Care was taken to avoid any contamination with fertilizer dust or other chemical or microbial contaminants. With the exception of the non-frozen samples, most samples were stored in the cloth bags in a -80°C freezer until all samples were collected and ready for analysis.

Soil Analysis

The soil was analyzed for a variety of chemical components at and in cooperation with the Brigham Young University—Environmental Analytical Laboratory (BYU—EAL; Table 2-1). Prior to analysis, the frozen samples were thawed and incubated, along with the non-frozen samples, for 14 d indoors at 20-22°C. The soil was kept slightly moist as needed to avoid excessive drying, while avoiding additions of excess water to avoid leaching of mobile nutrients. The remaining soil was dried and ground for chemical analyses.

Statistical Analysis

Differences with each soil parameter was evaluated by Analysis of Variance (ANOVA) with General Linear Models (GLM) with mean separation via the Tukey-Kramer method (JMP software). Additionally, the sports fields were combined for orthogonal comparisons with the other landscape types. The data was parsed to evaluate: painted vs. non-painted athletic fields, professional vs. collegiate, and frozen storage vs. non-frozen. The data was further evaluated by determining the correlations between all of the soil test parameters, including the soil health tests evaluated in Chapter 1.

RESULTS

Soil Properties

There were significant differences for the individual comparisons for pH, salts (EC), TN, P, K, Mg, Zn, Mn, and Cu, as well as Fe and Ca at an alpha level of 10% (Table 2-2). When combining sports field venues for orthogonal comparisons, the results were significant for these same parameters other than EC, K, and Ca. Average values, with mean separations for all venues with statistical differences, are shown in Figs. 2-1, 2-2, and 2-3 and for those without any significance in Table 2-3.

The bioavailable P, as measured by the Mehlich 3 extractant, was highly significant across landscape/venue types (Table 2-2; Fig. 2-1). In general, the sports field and golf course soils had soil P well above the critical value, along with the urban landscape samples. Football, soccer, baseball, and intermural had significantly higher P than the sand control, with the other landscape/venue types trending to being higher as well (Fig. 2-1i). When combined orthogonally, sport and golf venues were significantly higher than the sand control; however, urban, farm, and forest venues were not significantly different from sport venues or the sand control (Fig. 2-1ii).

There were significant differences for some of the other nutrients as well (Fig. 2-2), with the only clear pattern that the non-vegetated sand control was numerically the lowest than all other landscape/venues for all the nutrients. These differences were statistically significant in many cases, including: soccer for K (Fig. 2-2i); soccer, forest, baseball, and football for Zn (Fig. 2-2iii); all venues except intermural for Cu (Fig. 2-2v); all venues except farm, forest, and intermural for Mn (Fig. 2-2iv); and all venues for Fe (Fig. 2-2vi). When sports fields were all combined, they had significantly higher levels than the sand control for Zn, Cu, Mn, and Fe but not K or Mg (Fig. 2-3).

Besides these differences with the sand control, the only other differences with nutrients for individual comparisons was with Mg (Fig. 2-2ii). Farm and golf were significantly higher in Mg than baseball and football; and soccer was higher than football. When combining sports fields, farm and golf were significantly higher for Mg. And farm and forest were significantly higher in Mn than sports fields.

There were also significant differences for pH (Table 2-2). The pH of the sand control is significantly higher than sport, forest, and urban venues (Fig. 2-4). And golf was significantly higher in TN than football and the sand control. When combined orthogonally, golf and forest soils were higher in TN than sport and the sand control.

Correlations

The majority of parameters evaluated were positively correlated with each other, as well as with the soil health parameters reported in Chapter 1 (Table 2-4). To simplify Table 2-4 somewhat, we did not include total and stable aggregate correlations because they did not correlate with any of the soil fertility measurements.

Not surprisingly, the salts (EC) and the concentrations of all of the more soluble/mobile nutrients (K, S, Ca, Mg, and B) decreased as sand content increased (and clay and silt decreased). The less soluble/mobile nutrients generally were not correlated (P, Zn, and Fe), although there was similar correlation with Mn and Cu. Also not surprisingly, as pH increased the salts (EC) and the concentrations of Ca and Mg increased while Fe decreased. The pH was not correlated to any soil health or other parameter except unstable aggregates, which increased with increasing pH and EC. In addition to being positively correlated with pH, the salt concentration (EC) was positively correlated with all of the nutrients except P and Zn, which had no correlation, and Fe, which was negatively correlated. The EC was also positively correlated with all of the soil health parameters except fraction of aggregates and ACE protein.

In general, nutrient concentrations were positively correlated to each other (Table 2-4). The TN was correlated positively to nearly every measured parameter, including soil health, with the exceptions of P, Fe, pH, and the aggregates. The K concentrations were similar, except it was not correlated to Zn and Fe concentrations, nor the aggregates or ACE protein. The Ca concentrations were similar except with P and B concentrations and ACE protein, and having negative correlations with Fe and the fraction of stable aggregates. The Mg was similar, although it did have a correlation with B, but not Zn. The S was positively correlated to TN, K, Ca, and Mg concentrations, as well as TC, TOC, POxC, CO2, and BG. The B concentrations were positively correlated to TN, K, Mg, and TIC concentrations, as well as most of the soil health parameters except aggregates and ACE protein. The Cu concentrations were positively correlated to nearly everything except S and B concentrations, and it was also not correlated to aggregates, CO2 respiration, and BG. The Mn was correlated to TN, K, Ca, Mg, Zn, Cu, and TC and TOC concentrations, as well as POxC, BG, and ACE protein. The Mn was correlated to positively to unstable aggregates, with a negative correlation with the fraction of stable aggregates. The Zn was correlated to TN, Ca, Mn, Cu, and all of the C measures, including POxC. However, the P had the least amount of correlation, as it was only correlated to K, Fe, and Cu. Notably, it was not correlated to any of the soil health parameters.

Effect of Paint, Sport Level, and Sample Storage

There were no significant differences in any of the soil properties between samples that had been frozen and those that had not, except in the case of Zn which was significantly higher in frozen samples than in non-frozen samples (Table 2-5). There were few significant differences in soil samples taken in professional sport fields and those taken in collegiate fields, with the exception of EC and TN, which were both significantly higher in collegiate fields than in professional fields (Table 2-6). And, similar to the soil health parameters (see Chapter 1), there were no statistically significant differences for painted vs. non-painted soils (Table 2-7).

DISCUSSION

Soil Nutrients

Soil testing is a reliable method to determine nutrient bioavailability, with a focus on avoiding deficiencies while not grossly exceeding optimal levels (Hopkins and Hansen, 2019; Hopkins 2020; Thompson et al., 2023). Some nutrients (such as K, Ca, and Mg) often exhibit excesses without major issues (Kobayashi, 2005). However, excesses of N, P, S, Zn, Fe, Mn, Cu, and B can harm plants, the environment, and resource efficiency (Barben et al., 2011; LeMonte et al 2016, 2018; Ransom et al 2020; Hopkins 2015, 2020). Excesses are also known to be harmful to the environment for N (LeMonte et al. 2016), P (Hopkins and Hansen 2019), Zn (Nichols et al 2012, Christensen and Jackson 1981), Mn (Huang et al 2016), Cu (Zhang et al. 2019, Hill et al.1979), B (Allison et al. 1954), and Cl (Rhodes 1982). In general, excesses are also wasteful of natural resources used as raw materials, as well as fossil fuels used in their manufacture and/or transportation (Hopkins 2020).

Soluble nutrients (K, S, B) are readily leached through soil, especially heavily irrigated sandy soils common in sports fields and golf courses. These showed minimal accumulation due to low soil retention capacities. In contrast, the poorly soluble nutrients (P, Zn, Fe, Mn, Cu) accumulated, particularly in sports fields. Although found at elevated levels in the soil, the micronutrients were generally within safe ranges. The study identified strong correlations between plant nutrients and soil biological factors, emphasizing the influence of management practices on soil health. This research sets the foundation for further investigations into soil management in urban systems.

Soil Fertility in Sports Fields

The average fertility measurements for sport fields were not generally a problem. Levels of pH and salts were in normal, healthy ranges; most nutrients were as well, although Zn was borderline deficient in some types; Mg is very high in some cases, but this is not likely a problem and is likely due to natural soil and/or irrigation water chemistry rather than due to fertilization.

The fertilized venues were generally higher in the poorly soluble and relatively immobile nutrients (P, Zn, Fe, Mn, Cu) and lower in pH than the sand control. Somewhat surprisingly, the non-fertilized forest was generally equivalent to the fertilized venues in Mehlich 3 extracted nutrients. The farm samples averaged higher Mn and Mg than sports fields. Golf was higher than sports fields and the forest samples were higher than sports and the sand control. The data generated in this project suggests that the more soluble nutrients that were measured (K, S, and B) did not accumulate in fertilized soils compared to non-fertilized. Many sports fields and golf greens/tee boxes have a high level of sand (Supplemental Fig 1-1.). Sand and silt particles have low CEC compared to clays and, thus, tend to absorb cations. Due to the low CEC, the K was not as likely to stay resident in soils. The B and S exist in soils as anions and, because soils are also negatively charged, these (along with nitrate-N not measured in this study) are repelled by the soil CEC and, as such, easily leached out of the root zone.

In contrast, the poorly soluble nutrients measured in this study (P, Zn, Fe, Mn, and Cu) accumulated. In some cases (P, N, K, Mg, Zn, Mn, Cu), these were significantly higher than some non-fertilized and even fertilized venues. All of the sports fields had higher micronutrients with low solubility (Zn, Fe, Mn, Cu) than the sand control, which is the trend that we expected to see due to fertilization. None of the venue types were measured within toxic ranges, suggesting that micronutrients are well-managed in sports fields and golf courses. Since soccer was the only venue that was higher in K than the sand control, with all other venues possessing similar results, we concluded that K was not significantly affected by management practices. Optimal micronutrient and K fertilization has been studied and well documented, making the information more accessible to land managers (Thompson et al. 2023). Mg, EC, and pH followed similar trends.

Phosphorus Levels

Sport and urban venues were particularly high in P, suggesting that managers are applying a lot of P fertilizer. P has a low solubility in soil, resulting in accumulation with each application, resulting in high soil P levels. Recent studies have shown a need for recalibration of soil test P critical levels and suggest the need for P to be applied more efficiently (Hopkins and Hansen 2019). Additionally, other studies have shown the detrimental effects of applying excess fertilizer on the environment, from P surpluses in water and soil systems to decreased crop production (MacDonald et al. 2011, Sattari et al. 2012). High levels of P can potentially cause micronutrient deficiencies. Additionally rigorous application of P can result in environmental contamination of surface water bodies, leading to eutrophication in some cases. Excess P application is also wasteful of the natural resources used to manufacture P fertilizer, and favors weed, particularly annual bluegrass (*Poa annua) growth*. Sport field managers should fertilize with P based on soil testing. Observing and managing other nutrients with good correlations between soil tests and plant response can also increase the productivity of a soil system without having detrimental effects. Future research comparing plant health with sport fields with high, optimal, and low P levels should be performed to study what happens with time as fertilizer P is no longer applied to these fields with high P concentrations.

Correlations with Soil Health Metrics

The relationship between soil chemistry and soil biological health is a well-studied area in soil science. Soil chemistry [e.g., nutrient availability, pH, and organic matter (OM)] can significantly impact the diversity and activity of soil microorganisms, which in turn influence soil health. While we saw high correlations between soil chemical and biological characteristics, more research should be done to determine if these correlations are cause and effect.

In terms of correlations between chemical, biological, and physical analyses, we found high correlations between plant nutrients and soil biological factors. This finding supports other research that found that management practices, including pesticides and fertilizer application, influenced soil biological and physical health, suggesting an interplay of chemicals added during fertilization and soil biological activity (Liu et al. 2011). Overall, these correlations present a need to look at the interactions between fertilizer application and soil microbial activity in more depth. This study is a baseline to propel other research on soil management in urban systems.

Not surprisingly, the salts (EC) and the concentrations of all of the more soluble/mobile nutrients (K, S, Ca, Mg, and B) decreased as sand content increased (and clay and silt decreased). The less soluble/mobile nutrients generally were not correlated (P, Zn, and Fe), although there was similar correlation with Mn and Cu.

CONCLUSIONS

The primary objective of this study was aimed to assess soil fertility in terms of chemical properties and their availability across various landscapes, including managed sports fields and golf courses, native ecosystems, farm fields, and non-sport urban environments. High soil P values with potentially negative effects were observed in sport samples. We did not find any reason to classify the sports field soils with poor soil fertility. In most cases, all of the soils that had actively growing plants had mostly similar levels of soil fertility. This is in contrast with comparison to sand control soils without any vegetation. The fertilized venues were generally higher in the poorly soluble and relatively immobile nutrients (P, Zn, Fe, Mn, Cu) and lower in pH than the sand control. This research shows the importance of field managers being conscious of the amount of fertilizers used to maintain soil fertility. Future research comparing plant health with sport fields with high, optimal, and low nutrients should be done to study what happens with time as fertilizer nutrients are no longer applied to these fields with high concentrations, and what happens when those levels are lower than plant requirements.

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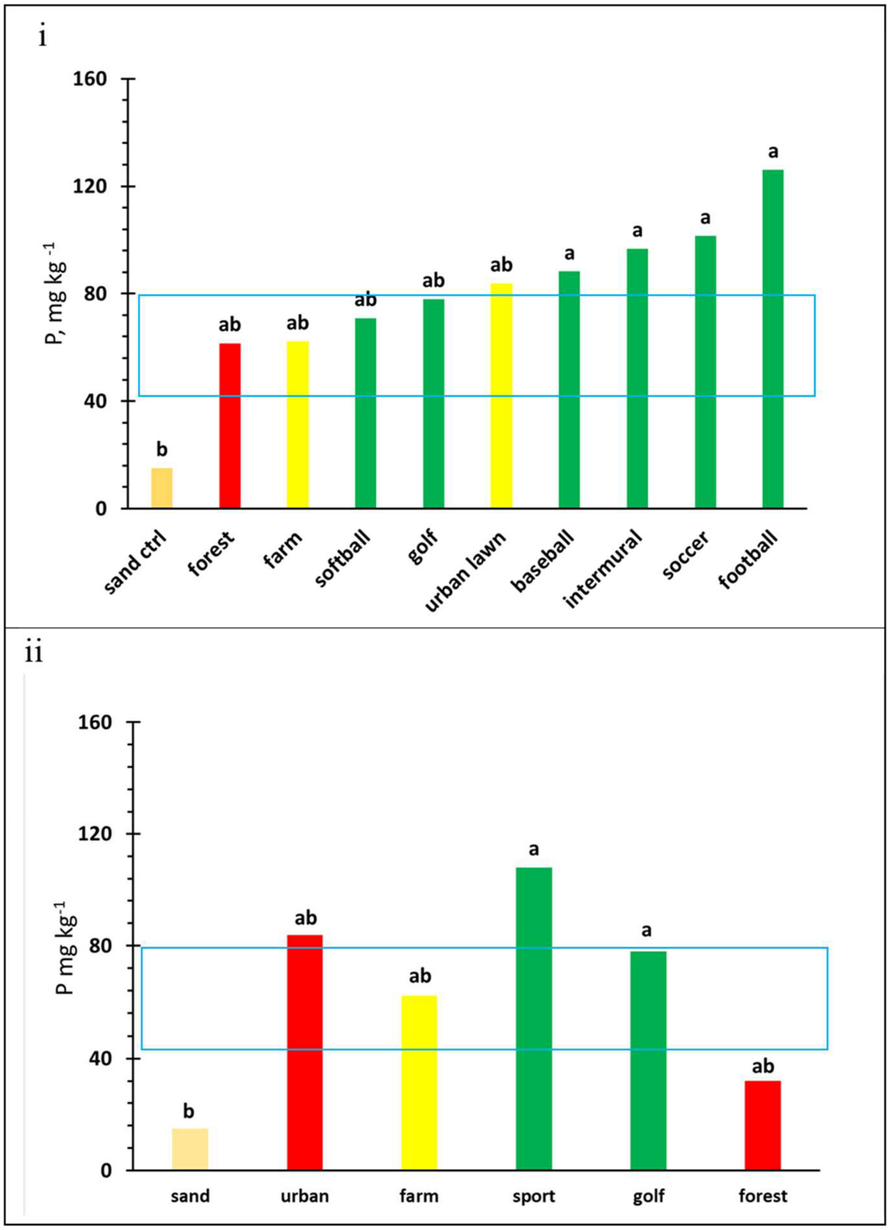

Figure 2-1. Bioavailable (Mehlich III extraction) soil phosphorus (P) for individual (i), as well as orthogonally combined (ii), sports fields. The sports fields and golf courses (green bars) are compared to other managed landscapes (yellow bars), as well as unmanaged vegetated forest soils (red bar) and non-vegetated sandy soils (tan bar). The range of values within the blue box represents typical P sufficiency levels. Landscape types sharing the same letter(s) are not statistically different than one another. (P=0.05).

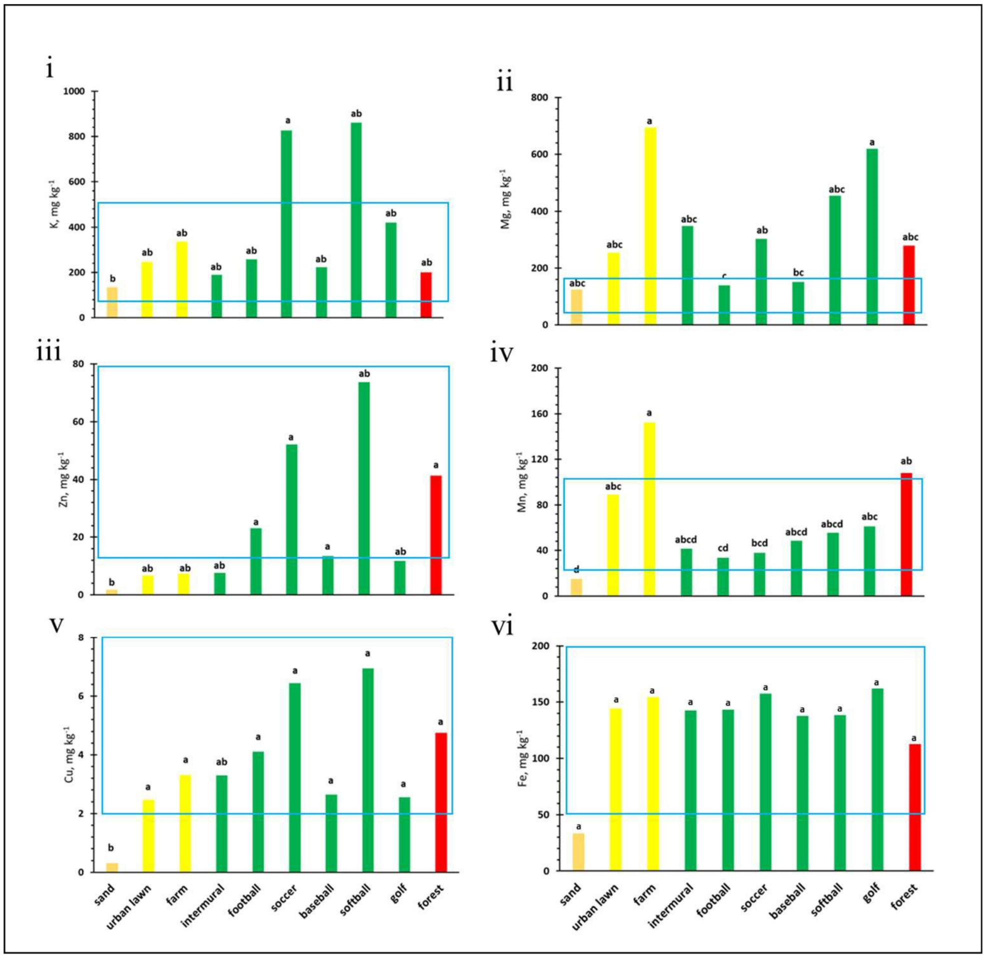

Figure 2-2. Bioavailable (Mehlich 3 extraction) soil potassium (K, i), magnesium (Mg, ii), zinc (Zn, iii), manganese (Mn, iv), copper (Cu, v), and iron (Fe, vi) for sports fields and golf courses (green bars) compared to other managed landscapes (yellow bars), as well as unmanaged vegetated forest soils (red bars) and non-vegetated sandy soils (tan bars). The range of values within each blue box represents typical sufficiency levels. Landscape types sharing the same letter(s) are not statistically different than one another. (P=0.05)

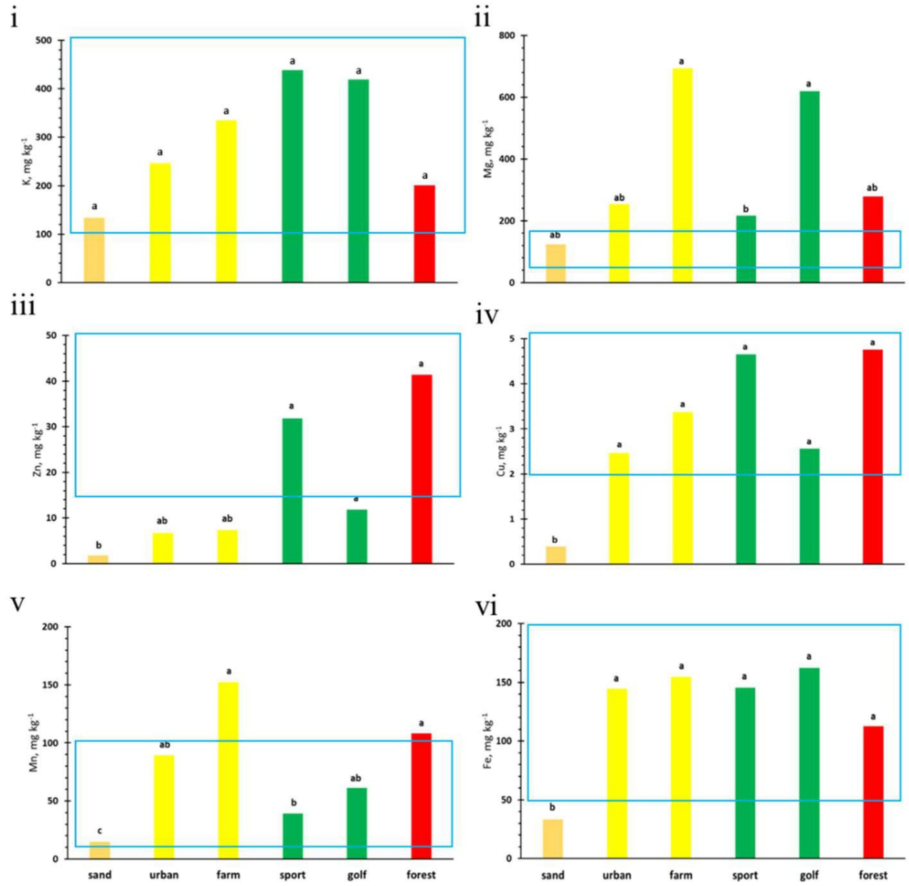

Figure 2-3. Bioavailable (Mehlich 3 extraction) soil potassium (K, i), magnesium (Mg, ii), zinc (Zn, iii), manganese (Mn, iv), copper (Cu, v), and iron (Fe, vi) for sports fields (combined orthogonally across various sport types) and golf courses (green bars) compared to other managed landscapes (yellow bars), as well as unmanaged vegetated forest soils (red bars) and non-vegetated sandy soils (tan bars). The range of values within each blue box represents typical sufficiency levels. Landscape types sharing the same letter(s) are not statistically different than one another. (*P*=0.05)

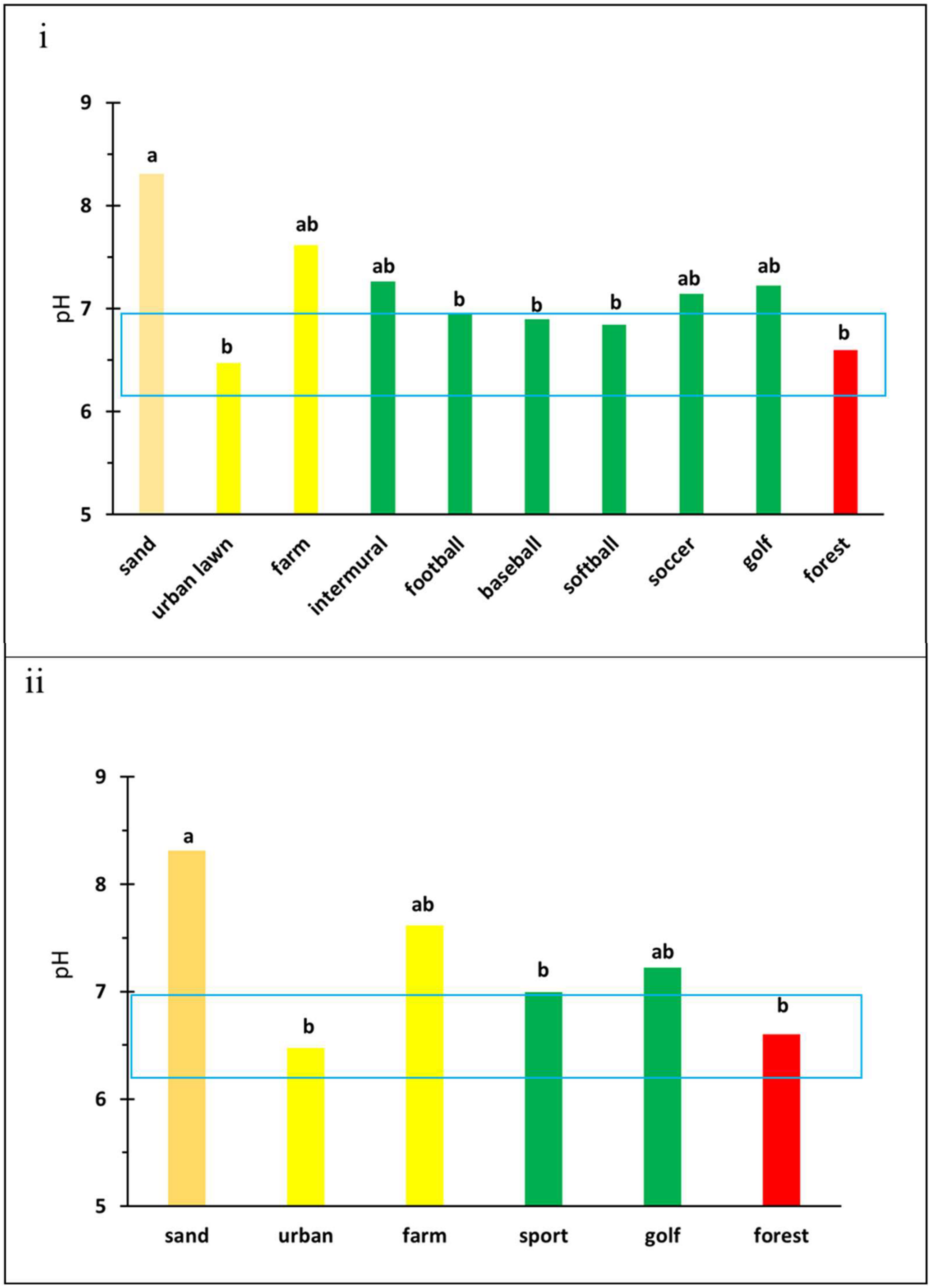

Figure 2-4. Soil pH for individual (i) and orthogonally combined (ii) sports fields and golf courses (green bars) compared to other managed landscapes (yellow bars), as well as unmanaged vegetated forest soils (red bars) and non-vegetated sandy soils (tan bars). The range of values within the blue box represents typical pH levels. Landscape types sharing the same letter(s) are not statistically different than one another. (*P*=0.05)

TABLES

Table 2-1. Methods of analysis.

pH by 1:1 paste	Rhodes 1982
Soluble Salts by electrical conductivity (EC)	Rhodes 1982
Total Nitrogen by combustion[1]	Stott 2019
Phosphorus (P), Potassium (K), Sulfur (S), Calcium (Ca), Magnesium (Mg), Zinc (Zn), Iron (Fe), Manganese (Mn), Copper (Cu), Boron (B) by Mehlich III extraction[1]	Gaviak et al. 2005

[1] Elementar, VarioELCube, Ronkonkoma, NY, USA
[2] ThermoScientific, ICAP7400Radial, Waltham, MA, USA

Table 2-2. Statistical significance (*P*-values) comparing individual sports to each other and other landscape types, as well as orthogonal comparisons with all sports combined and compared to other landscape types.

Analyte	Individual Comparisons	Orthogonal Comparisons
pH	0.0023	0.0002
soluble salts (EC)	0.0219	0.1769
Nitrogen (N)	0.0019	0.0035
Phosphorous (P)	0.0221	0.0059
Potassium (K)	0.0191	0.1504
Sulfur (S)	0.2990	0.3560
Calcium (Ca)	0.0568	0.2320
Magnesium (Mg)	0.0001	0.0017
Zinc (Zn)	0.0032	0.0071
Iron (Fe)	0.0925	0.0010
Manganese (Mn)	< 0.0001	< 0.0001
Copper (Cu)	0.0003	0.0002
Boron (B)	0.9385	0.8254

Table 2-3. Mean values for electrical conductivity (EC) and bioavailable (Mehlich 3 extraction) sulfur (S), calcium (Ca), and boron (B). Differences were not statistically significant. (P = 0.05)

Venue	EC	S	Ca	B
	μmhos cm^{-1}	---------	mg kg^{-1}	---------
Sand	192	11	1601	15
Urban Lawn	363	33	1677	15
Farm	442	38	3316	15
Intermural	316	22	5052	14
Football	186	14	1191	14
Soccer	364	29	2247	14
Baseball	206	22	1353	15
Softball	575	150	2471	14
Golf	277	25	2456	16
Forest	193	13	2948	14

Table 2-4. Correlations between soil metrics based on Pairwise and Correlation Probability statistics. Shaded values are significant (P = 0.05).

correlations estimated by Pairwise method

	TN	P	K	S	Ca	Mg	Zn	Fe	Mn	Cu	B	pH	EC	Sand	Clay	Silt	unstable	aggregate fractior	PMN	POxC	CO2	BG	ACE	TIC	TC	TOC
TN		-0.0021	0.5525	0.3232	0.5275	0.5989	0.2161	-0.0681	0.289	0.3023	0.2278	0.0455	0.5819	-0.4357	0.3788	0.443	0.0572	-0.0075	0.6754	0.5928	0.6166	0.6516	0.3974	0.4944	0.8246	0.6914
P	-0.0021		0.1936	0.001	-0.0946	-0.0527	0.0284	0.3924	-0.0886	0.3993	-0.0645	-0.0762	0.0115	0.1474	-0.1202	-0.1546	-0.1684	0.088	0.0019	-0.0812	-0.0419	-0.0076	-0.0711	0.0581	-0.0092	-0.0967
K	0.5525	0.1936		0.2738	0.5036	0.7415	0.1103	-0.0907	0.3147	0.3074	0.1974	0.1697	0.6203	-0.4643	0.4593	0.4382	0.1682	-0.1228	0.6944	0.4683	0.6353	0.676	0.126	0.3692	0.5864	0.4639
S	0.3232	0.001	0.2738		0.4725	0.4788	-0.0049	-0.1349	0.0316	0.0579	0.1768	0.1253	0.7365	-0.2974	0.3872	0.2239	0.0109	0.022	0.1726	0.2922	0.2123	0.2387	-0.0556	0.1405	0.2753	0.2553
Ca	0.5275	-0.0946	0.5036	0.4725		0.6601	0.2435	-0.3454	0.2367	0.2487	0.1339	0.4806	0.684	-0.4343	0.4558	0.394	0.2681	-0.247	0.3738	0.3342	0.4228	0.4953	0.0297	0.4856	0.6371	0.4139
Mg	0.5989	-0.0527	0.7415	0.4788	0.6601		0.096	-0.2669	0.4514	0.3014	0.2731	0.3371	0.6812	-0.6493	0.613	0.6307	0.3857	-0.2455	0.5241	0.4033	0.5458	0.671	0.059	0.3162	0.5846	0.5257
Zn	0.2161	0.0284	0.1103	-0.0049	0.2435	0.096		-0.0566	0.3199	0.5107	0.0282	0.1329	0.0929	-0.0771	0.0777	0.0719	0.0551	-0.162	0.1096	0.2447	0.1287	0.0651	0.0839	0.2385	0.2462	0.4129
Fe	-0.0681	0.3924	-0.0907	-0.1349	-0.3454	-0.2669	-0.0566		-0.1148	0.2448	0.1146	-0.4281	-0.253	0.0608	-0.0618	-0.0564	-0.1849	0.2206	0.0542	0.0075	0.0184	-0.0561	0.1183	-0.0673	-0.0944	-0.0829
Mn	0.289	-0.0886	0.3147	0.0316	0.2367	0.4514	0.3199	-0.1148		0.3744	0.0208	0.1769	0.2392	-0.5911	0.5039	0.6072	0.4993	-0.3476	0.1691	0.2928	0.1832	0.252	0.3439	-0.0466	0.1854	0.3929
Cu	0.3023	0.3993	0.3074	0.0579	0.2487	0.3014	0.5107	0.2448	0.3744		0.1706	0.0826	0.1978	-0.2302	0.2128	0.2264	0.089	-0.1021	0.1931	0.2138	0.1577	0.175	0.1939	0.3127	0.3421	0.198
B	0.2278	-0.0645	0.1974	0.1768	0.1339	0.2731	0.0282	0.1146	0.0208	0.1706		0.0553	0.2936	-0.1674	0.1956	0.1397	0.0469	0.1309	0.2451	0.1873	0.225	0.2036	0.0116	0.0874	0.1977	0.2003
pH	0.0455	-0.0762	0.1697	0.1253	0.4806	0.3371	0.1329	-0.4281	0.1769	0.0826	0.0553		0.2299	-0.0143	0.0056	0.0187	0.1967	-0.1841	0.0291	0.0271	0.1123	0.1661	-0.1846	0.0915	0.1232	0.0923
EC	0.5819	0.0115	0.6203	0.7365	0.684	0.6812	0.0929	-0.253	0.2392	0.1978	0.2936	0.2299		-0.4679	0.5249	0.4038	0.1943	-0.1781	0.4482	0.3881	0.4289	0.4806	0.0637	0.3329	0.5617	0.4665
Sand	-0.4357	0.1474	-0.4643	-0.2974	-0.4343	-0.6493	-0.0771	0.0608	-0.5911	-0.2302	-0.1674	-0.0143	-0.4679		-0.9356	-0.9765	-0.6408	0.3288	-0.3385	-0.2562	-0.3488	-0.3489	-0.1827	-0.1079	-0.3541	-0.4268
Clay	0.3788	-0.1202	0.4593	0.3872	0.4558	0.613	0.0777	-0.0618	0.5039	0.2128	0.1956	0.0056	0.5249	-0.9356		0.8376	0.5699	-0.2918	0.3248	0.178	0.3334	0.2811	0.1502	0.0552	0.3102	0.4271
Silt	0.443	-0.1546	0.4382	0.2239	0.394	0.6307	0.0719	-0.0564	0.6072	0.2264	0.1397	0.0187	0.4038	-0.9765	0.8376		0.6439	-0.3308	0.3254	0.2887	0.3363	0.3684	0.1911	0.1333	0.3586	0.4
unstable	0.0572	-0.1684	0.1682	0.0109	0.2681	0.3857	0.0551	-0.1849	0.4993	0.089	0.0469	0.1967	0.1943	-0.6408	0.5699	0.6439		-0.7425	-0.0744	0.0022	0.0451	0.1549	-0.0949	-0.0526	-0.0103	0.0775
aggregate fractions	-0.0075	0.088	-0.1228	0.022	-0.247	-0.2455	-0.162	0.2206	-0.3476	-0.1021	0.1309	-0.1841	-0.1781	0.3288	-0.2918	-0.3308	-0.7425		0.1345	0.1029	-0.008	-0.0954	0.151	-0.0189	0.0262	0.0169
PMN	0.6754	0.0019	0.6944	0.1726	0.3738	0.5241	0.1096	0.0542	0.1691	0.1931	0.2451	0.0291	0.4482	-0.3385	0.3248	0.3254	-0.0744	0.1345		0.5971	0.8078	0.7086	0.3283	0.274	0.6188	0.6232
POxC	0.5928	-0.0812	0.4683	0.2922	0.3342	0.4033	0.2447	0.0075	0.2928	0.2138	0.1873	0.0271	0.3881	-0.2562	0.178	0.2887	0.0022	0.1029	0.5971		0.5873	0.5433	0.2239	0.2717	0.5417	0.5289
CO2	0.6166	-0.0419	0.6353	0.2123	0.4228	0.5458	0.1287	0.0184	0.1832	0.1577	0.225	0.1123	0.4289	-0.3488	0.3334	0.3363	0.0451	-0.008	0.8078	0.5873		0.7517	0.1327	0.2777	0.5493	0.5229
BG	0.6516	-0.0076	0.676	0.2387	0.4953	0.671	0.0651	-0.0561	0.252	0.175	0.2036	0.1661	0.4806	-0.3489	0.2811	0.3684	0.1549	-0.0954	0.7086	0.5433	0.7517		0.0989	0.376	0.598	0.4706
ACE	0.3974	-0.0711	0.126	-0.0556	0.0297	0.059	0.0839	0.1183	0.3439	0.1939	0.0116	-0.1846	0.0637	-0.1827	0.1502	0.1911	-0.0949	0.151	0.3283	0.2239	0.1327	0.0989		0.0146	0.3965	0.6047
TIC	0.4944	0.0581	0.3692	0.1405	0.4856	0.3162	0.2385	-0.0673	-0.0466	0.3127	0.0874	0.0915	0.3329	-0.1079	0.0552	0.1333	-0.0526	-0.0189	0.274	0.2717	0.2777	0.376	0.0146		0.7663	-0.0183
TC	0.8246	-0.0092	0.5864	0.2753	0.6371	0.5846	0.2462	-0.0944	0.1854	0.3421	0.1977	0.1232	0.5617	-0.3541	0.3102	0.3586	-0.0103	0.0262	0.6188	0.5417	0.5493	0.598	0.3965	0.7663		0.6207
TOC	0.6914	-0.0967	0.4639	0.2553	0.4139	0.5257	0.4129	-0.0829	0.3929	0.198	0.2003	0.0923	0.4665	-0.4268	0.4271	0.4	0.0775	0.0169	0.6232	0.5289	0.5229	0.4706	0.6047	-0.0183	0.6207	

Correlation Probability

	TN	P	K	S	Ca	Mg	Zn	Fe	Mn	Cu	B	pH	EC	Sand	Clay	Silt	unstable	aggregate fractior	PMN	POxC	CO2	BG	ACE	TIC	TC	TOC
TN		0.9823	<.0001	0.0006	<.0001	<.0001	0.0234	0.4794	0.0022	0.0013	0.0167	0.637	<.0001	<.0001	<.0001	<.0001	0.5582	0.9382	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
P	0.9823		0.0427	0.9914	0.3254	0.5845	0.7681	<.0001	0.3571	<.0001	0.5035	0.4288	0.9048	0.1336	0.2218	0.1152	0.083	0.3652	0.9846	0.4055	0.665	0.9373	0.4645	0.5467	0.9238	0.3193
K	<.0001	0.0427		0.0038	<.0001	<.0001	0.2512	0.3462	0.0008	0.0011	0.0387	0.0763	<.0001	<.0001	<.0001	<.0001	0.0833	0.2056	<.0001	<.0001	<.0001	<.0001	0.1937	<.0001	<.0001	<.0001
S	0.0006	0.9914	0.0038		<.0001	<.0001	0.9599	0.1599	0.7428	0.548	0.0647	0.1922	<.0001	0.0021	<.0001	0.0217	0.9114	0.8215	0.0755	0.0023	0.0267	0.012	0.5675	0.1431	0.0036	0.0077
Ca	<.0001	0.3254	<.0001	<.0001		<.0001	0.0104	0.0002	0.0128	0.0088	0.1631	<.0001	<.0001	<.0001	<.0001	<.0001	0.0052	0.01	<.0001	0.0004	<.0001	<.0001	0.7605	<.0001	<.0001	<.0001
Mg	<.0001	0.5845	<.0001	<.0001	<.0001		0.3183	0.0048	<.0001	0.0014	0.0039	0.0003	<.0001	<.0001	<.0001	<.0001	<.0001	0.0104	<.0001	<.0001	<.0001	<.0001	0.5441	0.0008	<.0001	<.0001
Zn	0.0234	0.7681	0.2512	0.9599	0.0104	0.3183		0.5573	0.0007	<.0001	0.7701	0.1663	0.3344	0.4343	0.4306	0.4661	0.5732	0.0939	0.261	0.0111	0.1824	0.4995	0.3879	0.0121	0.0095	<.0001
Fe	0.4794	<.0001	0.3462	0.1599	0.0002	0.0048	0.5573		0.2323	0.01	0.2334	<.0001	0.0077	0.538	0.5314	0.568	0.0565	0.0218	0.5795	0.9389	0.8492	0.5603	0.2227	0.4847	0.3266	0.3937
Mn	0.0022	0.3571	0.0008	0.7428	0.0128	<.0001	0.0007	0.2323		<.0001	0.8295	0.0645	0.0119	<.0001	<.0001	<.0001	<.0001	0.0002	0.0816	0.0022	0.0566	0.0079	0.0003	0.629	0.0525	<.0001
Cu	0.0013	<.0001	0.0011	0.548	0.0088	0.0014	<.0001	0.01	<.0001		0.0748	0.3911	0.0383	0.0181	0.0293	0.0202	0.362	0.2932	0.0463	0.027	0.1015	0.0675	0.0444	0.0009	0.0003	0.0399
B	0.0167	0.5035	0.0387	0.0647	0.1631	0.0039	0.7701	0.2334	0.8295	0.0748		0.566	0.0019	0.0878	0.0455	0.1552	0.6316	0.1769	0.0109	0.0534	0.0187	0.0329	0.9054	0.3641	0.0384	0.0377
pH	0.637	0.4288	0.0763	0.1922	<.0001	0.0003	0.1663	<.0001	0.0645	0.3911	0.566		0.0157	0.8847	0.9548	0.8495	0.0423	0.0565	0.7663	0.7817	0.2451	0.0829	0.0559	0.3419	0.1996	0.3418
EC	<.0001	0.9048	<.0001	<.0001	<.0001	<.0001	0.3344	0.0077	0.0119	0.0383	0.0019	0.0157		<.0001	<.0001	<.0001	0.0449	0.0652	<.0001	<.0001	<.0001	<.0001	0.5125	0.0004	<.0001	<.0001
Sand	<.0001	0.1336	<.0001	0.0021	<.0001	<.0001	0.4343	0.538	<.0001	0.0181	0.0878	0.8847	<.0001		<.0001	<.0001	<.0001	0.0006	0.0005	0.0093	0.0003	0.0003	0.0647	0.2731	0.0002	<.0001
Clay	<.0001	0.2218	<.0001	<.0001	<.0001	<.0001	0.4306	0.5314	<.0001	0.0293	0.0455	0.9548	<.0001	<.0001		<.0001	<.0001	0.0025	0.0009	0.0735	0.0005	0.0037	0.13	0.5759	0.0013	<.0001
Silt	<.0001	0.1152	<.0001	0.0217	<.0001	<.0001	0.4661	0.568	<.0001	0.0202	0.1552	0.8495	<.0001	<.0001	<.0001		<.0001	0.0006	0.0008	0.0032	0.0005	0.0001	0.0532	0.1752	0.0002	<.0001
unstable	0.5582	0.083	0.0833	0.9114	0.0052	<.0001	0.5732	0.0565	<.0001	0.362	0.6316	0.0423	0.0449	<.0001	<.0001	<.0001		<.0001	0.4528	0.9826	0.6446	0.1112	0.3357	0.5908	0.9165	0.4321
aggregate fractions	0.9382	0.3652	0.2056	0.8215	0.01	0.0104	0.0939	0.0218	0.0002	0.2932	0.1769	0.0565	0.0652	0.0006	0.0025	0.0006	<.0001		0.1714	0.2965	0.9345	0.3258	0.1222	0.8464	0.7875	0.8634
PMN	<.0001	0.9846	<.0001	0.0755	<.0001	<.0001	0.261	0.5795	0.0816	0.0463	0.0109	0.7663	<.0001	0.0005	0.0009	0.0008	0.4528	0.1714		<.0001	<.0001	<.0001	0.0006	0.0043	<.0001	<.0001
POxC	<.0001	0.4055	<.0001	0.0023	0.0004	<.0001	0.0111	0.9389	0.0022	0.027	0.0534	0.7817	<.0001	0.0093	0.0735	0.0032	0.9826	0.2965	<.0001		<.0001	<.0001	0.0217	0.0046	<.0001	<.0001
CO2	<.0001	0.665	<.0001	0.0267	<.0001	<.0001	0.1824	0.8492	0.0566	0.1015	0.0187	0.2451	<.0001	0.0003	0.0005	0.0005	0.6446	0.9345	<.0001	<.0001		<.0001	0.1731	0.0035	<.0001	<.0001
BG	<.0001	0.9373	<.0001	0.012	<.0001	<.0001	0.4995	0.5603	0.0079	0.0675	0.0329	0.0829	<.0001	0.0003	0.0037	0.0001	0.1112	0.3258	<.0001	<.0001	<.0001		0.3086	<.0001	<.0001	<.0001
ACE	<.0001	0.4645	0.1937	0.5675	0.7605	0.5441	0.3879	0.2227	0.0003	0.0444	0.9054	0.0559	0.5125	0.0647	0.13	0.0532	0.3357	0.1222	0.0006	0.0217	0.1731	0.3086		0.8807	<.0001	<.0001
TIC	<.0001	0.5467	<.0001	0.1431	<.0001	0.0008	0.0121	0.4847	0.629	0.0009	0.3641	0.3419	0.0004	0.2731	0.5759	0.1752	0.5908	0.8464	0.0043	0.0046	0.0035	<.0001	0.8807		<.0001	0.8507
TC	<.0001	0.9238	<.0001	0.0036	<.0001	<.0001	0.0095	0.3266	0.0525	0.0003	0.0384	0.1996	<.0001	0.0002	0.0013	0.0002	0.9165	0.7875	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001		<.0001
TOC	<.0001	0.3193	<.0001	0.0077	<.0001	<.0001	<.0001	0.3937	<.0001	0.0399	0.0377	0.3418	<.0001	<.0001	<.0001	<.0001	0.4321	0.8634	<.0001	<.0001	<.0001	<.0001	<.0001	0.8507	<.0001	

Table 2-5. Average values for chemical tests with corresponding significance values for differences in soil samples that had undergone a period of freezing (Frozen) and those that did not (Non-Frozen).

Variable	Frozen	Non-Frozen	*P*-value
pH	7.35	7.38	*0.8282*
	|----------μmhos cm^{-1}	----------------	
Electrical Conductivity (EC)	334	486	*0.1171*
	------------- mg kg^{-1}	----------------- -	
Total Nitrogen (TN)	237,000	268,000	*0.5229*
Phosphorous (P)	65.6	49.9	*0.2664*
Potassium (K)	335	361	*0.6158*
Sulfur (S)	38.5	36.2	*0.7132*
Calcium (Ca)	3520	3470	*0.6932*
Magnesium (Mg)	291	345	*0.7151*
Zinc (Zn)	11.2	2.40	*<0.0001*
Iron (Fe)	112	98.5	*0.4796*
Manganese (Mn)	43.1	32.9	*0.0744*
Copper (Cu)	1.96	1.46	*0.1897*
Boron (B)	15.3	12.0	*0.1735*

Table 2-6. Average values for chemical tests with corresponding significance values for differences in soil samples taken in professional sport fields and those taken in collegiate fields.

Variable	Professional	Collegiate	*P*-value
pH	7.12	6.97	*0.3471*
	|----------µmhos cm^{-1}	....	
Electroconductivity EC	179	277	*0.0264*
	---------- mg kg^{-1}	....	
Total Nitrogen (TN)	123,000	192,000	*0.0117*
Phosphorous (P)	125	101	*0.4775*
Potassium (K)	228	280	*0.9178*
Sulfur (S)	19.0	23.9	*0.7587*
Calcium (Ca)	1250	1740	*0.9603*
Magnesium (Mg)	227	239	*0.7507*
Zinc (Zn)	9.60	10.4	*0.7299*
Iron (Fe)	160	148	*0.8096*
Manganese (Mn)	40.2	39.6	*0.7589*
Copper (Cu)	2.84	2.58	*0.6103*
Boron (B)	15.2	14.1	*0.1823*

Table 2-7. Average values for chemical tests with corresponding significance values for differences in soil samples taken in parts of sports fields that had regularly been painted and parts of the same fields that were not painted.

Variable	Paint	Non-Paint	*P*-value
pH	7.17	7.02	*0.4874*
	--------μmhos cm^{-1}	....	
Electroconductivity EC	183	194	*0.7244*
	---------- mg kg^{-1}	....	
Total Nitrogen (TN)	112,000	119,000	*0.8591*
Phosphorous (P)	176	146	*0.4635*
Potassium (K)	198	197	*0.6196*
Sulfur (S)	15.7	15.7	*0.7482*
Calcium (Ca)	1310	1510	*0.7143*
Magnesium (Mg)	110	128	*0.8275*
Zinc (Zn)	8.11	8.89	*0.7254*
Iron (Fe)	162	171	*0.7093*
Manganese (Mn)	33.1	42.9	*0.8497*
Copper (Cu)	2.35	2.68	*0.6616*
Boron (B)	12.5	15.6	*0.2095*