TRAFFIC TOLERANCE OF FINE FESCUES:

TECHNIQUES FOR SCREENING GERMPLASM

by

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ABSTRACT OF THE DISSERTATION

Traffic tolerance of fine fescues: Techniques for screening germplasm

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The term fine fescue refers to several *Festuca* spp. that have a very fine leaf texture compared to most other turfgrass species. These species are adapted to low-input management systems and have been used in mixtures with other cool-season grasses. However, fine fescues are not utilized to the same extent as other species partially due to their poor traffic tolerance and recuperative ability. Improvement in traffic tolerance of fine fescues would enable use of these grasses beyond turf systems that experience little to no traffic.

The purpose of this dissertation was to develop and evaluate germplasm screening techniques that improve selecting efficiency for traffic tolerant fine fescues. The specific objectives of this research were: i) to evaluate the effect of traffic form (abrasive wear vs. cleated traffic) and season (spring vs. summer vs. autumn) on the assessment of fine fescue traffic tolerance (Chapters 1 and 2); ii) to evaluate the effect of nitrogen fertilization and harvest time on cell wall composition of fine fescues (Chapters 3 and 4); iii) to investigate the correlation between cell wall composition and wear tolerance of fine

fescues; and iv) to develop near-infrared reflectance spectroscopy (NIRS) models to determine the cell wall composition of fine fescues.

For the first objective, the ability of fine fescue turf to maintain a dense cover depended on the specific traffic form and varied based on the season during which wear stress occurred. Abrasive wear, applied with Rutgers Wear Simulator, caused more thinning of the turf canopy than cleated traffic applied with the Cady Traffic Simulator. Thus, abrasive wear resulted in a greater separation among fine fescues based on the fullness of turf cover (FTC) and will likely improve selection efficiency compared to cleated traffic. The FTC response of fine fescues were more sensitive to traffic stress during summer because of the high disease pressure and heat stress. Screening for fine fescues for improved traffic tolerance during spring would probably be less biased and more effective at identifying tolerance to traffic within fine fescues because other abiotic or biotic stresses would be avoided or minimized. Abrasive wear was also effective in identifying cultivars that are susceptible to leaf bruising. Leaf bruising was more severe during summer and autumn due to the heat stress. However, leaf bruising response of fine fescue cultivars varied with the season; sheep fescue and strong creeping red fescue were more susceptible to leaf bruising during summer while Chewings fescue and slender creeping red fescue were more bruised during autumn. Thus, evaluation of this characteristic would need to be conducted in both the summer and autumn.

For the second objective, N fertilization was expected to alter cell wall composition as it promotes new leafy growth, which would be expected to have lower cell wall content. However, the effect of N fertilization on cell wall composition was not observed. Differences among three fine fescue species were significant and the ranking of total cell wall (TCW) content remained the same throughout the entire study: hard fescue > Chewings fescue > strong creeping red fescue. Harvest time (season) had a significant impact on cell wall composition; TCW content was greater in summer (August) compared to spring (May) and autumn (November). However, the relative ranking among five fine fescue species was consistent despite the fluctuation in concentration caused by the harvest time. The concentrations of TCW, hemicellulose, lignocellulose and cellulose from high to low were: Sheep fescue > hard fescue > Chewings fescue = slender creeping red fescue > strong creeping red fescue.

For the third objective, a general pattern between wear tolerance and verdure biomass and cell wall constituents of fine fescues were identified on an inter-specific level; improved wear tolerance was associated with greater verdure biomass, TCW, and lignocellulose content as well as reduced lignin content. Correlations were not as strong on an intra-specific level which is probably due, at least in part, to a narrower range of diversity for these characteristics within each species. The potential to improve wear tolerance by selecting for greater verdure biomass, TCW and lignocellulose contents appeared to be more promising for Chewings and strong creeping red fescues than hard fescue.

For the fourth objective, NIRS provided a relatively rapid and precise method of estimating total N ($R^2_{cal} > 0.93$) in the verdure at both the inter- and intra-specific levels. Due to the complexity of the constituents, the prediction accuracy was less favorable, but reliable, for TCW ($R^2_{cal} > 0.70$), lignocellulose ($R^2_{cal} > 0.78$) and hemicellulose ($R^2_{cal} > 0.79$) at the intra or inter specific level(s). Further development of these NIRS prediction models would facilitate future research that defines the correlation between cell constituents, such as total N and cell wall composition, and the traffic tolerance of fine fescues.

This research advanced our understanding of methods to assess the traffic tolerance of fine fescues. Screening efficacy and accuracy can be improved using abrasive wear during spring when confounding stresses are minimal. This research indicated traffic tolerance among fine fescue species is positively associated with verdure biomass and cell wall content. It is also possible to select traffic tolerant cultivars within each species based on these traits with considerable phenotypic variability in wear tolerance. The development of NIRS calibration models will facilitate future breeding applications to rapidly identify fine fescue cultivars with greater cell wall content. The findings from this research will contribute to the sustainability of the turfgrass industry by improving screening techniques for developing traffic tolerant fine fescues cultivars for use on low-input landscapes.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
ADF	Acid detergent fiber
ADFCP	Acid detergent fiber crude protein
ADIN	Acid detergent insoluble nitrogen
ADL	Acid detergent lignin
ANOVA	Analysis of variance
BTS	Brinkman traffic simulator
CTS	Cady traffic simulator
CP	Crude protein
CS	Cross validation
D.S.1	Differential-slip traffic simulator
DEI	Digestible energy intake
df	Degrees of freedom
DIA	Digital image analysis
DM	Dry matter
DMI	Dry matter intake
DNDF	Digestible neutral detergent fiber
FTC	Full of turf cover
GA-SCW	Georgia soil compaction wear simulator
INDF	Indigestible neutral detergent fiber
IVDMD	In vitro dry matter disappearance
LSD	Fisher's least significant difference
MAD	Modified acid detergent (fiber)
MAS	Months after seeding
MLR	Multiple linear regression
MSC	Multiplicative signal correction
MSR	Multispectral radiometer
n	Sample size
NDF	Neutral detergent fiber
NDFCP	Neutral detergent insoluble protein
NDVI	Normalized difference vegetation index
NPN	Non-protein nitrogen
NE-SCW	Nebraska soil compaction wear simulator
NIRS	Near-infrared reflectance spectroscopy
p	Probability
PCA	Principal component analysis
r^2	Coefficient of determination
R^2	Coefficient of multiple determination
RMSECV	Root means square error of cross-validation
RMSEP	Root mean square error of prediction
RPD	Residual prediction deviation
RWS	Rutgers wear simulator
SAS	Statistical analysis system

SD	Standard deviation
SECV	Standard error of cross-validation
SEP	Square error of prediction
SN	Soluble nitrogen
SNV	Standard normal variate
TCP	True crude protein
TCW	Total cell wall
TN	Total nitrogen
UTC	Uniformity of turf cover
VWC	Volumetric water content

CHAPTER 1 Literature Review

INTRODUCTION

Fine fescues (*Festuca* spp.) include several species that have relatively fine leaf texture compared to most other species. They have been considered as low-input species and have often been used in mixtures with other cool-season grasses. However, these species are not utilized to the same extent as other species partially due to their poor traffic tolerance and recuperative ability. A survey conducted by Yue et al. (2017) on American and Canadian consumers showed that many consumers are willing to pay more for low-maintenance grasses, and one of the most important attributes for consumers is the ability to withstand traffic. Improvement in traffic tolerance of fine fescues will enable greater use of these species by the turf industry.

Enhancing traffic tolerance and recuperative ability of fine fescues requires the development of germplasm screening methods to assess the response of fine fescues to traffic. Plant cell wall constituents were found to play an important role in determining plant tissue tensile stress, mechanical rigidity, and elasticity (Taiz and Zeiger, 2002). The initial research of Shearman and Beard (1975b) reported greater concentrations of cell wall constituents were associated with improved wear tolerance. Studies indicated that the correlation between cell wall constituents and wear tolerance varied with turfgrass species thus needs to be investigated on species-specific level (Shearman and Beard, 1975b; Canaway, 1978; Canaway, 1981; Bourgoun et al. 1985; Kilmartin, 1994; Trenholm et al. 2000; Brosnan et al., 2005; Den Haan et al., 2009; Dowgiewicz et al., 2011). Research is needed to investigate the correlation of cell wall constituents and wear tolerance between and within fine fescue species.

The determination of cell wall constituents using conventional analytical methods can be time-consuming. Near-infrared reflectance spectroscopy (NIRS) provides a non-destructive, rapid and precise technique to determine the quality constituents of agricultural products. (Norris et al., 1976). The development of an accurate and precise NIRS equation could facilitate the determination of cell wall composition.

The purposes of this chapter are to: i) review the management, utilization, and traffic tolerance of fine fescues; ii) identify the correlation between cell wall constituents and traffic tolerance; and iii) discuss the use of NIRS to determine cell wall content of fine fescue.

FINE FESCUE

Fine fescues (*Festuca* spp.) are a group of fine-leafed cool-season turfgrass species that have been used in the turf industry since the sixteenth century (Schmit et al., 1974). The origin of *Festuca* spp. is reported to be central Europe, but these species are now adapted to diverse temperate regions of the world (Beard, 2014).

There are two main categories or complexes of fine fescues, the *F. rubra* (red fescue) complex and *F. ovina* (sheep fescue) complex (Ruemmele et al. 1995). The *F. rubra* complex consists of strong creeping red fescue (*F. rubra* ssp. *rubra* Gaudin), slender creeping red fescue [*F. rubra* ssp. *littoralis* (G. Mey.) Auquier], and Chewings fescue [*F. rubra* ssp. *commutata* Gaudin; syn. *F. rubra* ssp. *fallax* (Thuill.) Nyman]. *F. rubra* ssp. *commutata* has a bunch-type, non-rhizomatous growth habit, while *F. rubra* ssp. *littoralis* and *F. rubra* ssp. *rubra* produce rhizomes, with the latter having longer and more robust rhizomes. The *F. ovina* complex consists of hard fescue (*F. brevipila* Tracey) and sheep fescue [*F. ovina* L.; syn. *F. ovina* ssp. *hirtula* (Hack. ex Travis) M.J. Wilk.], both of which have a bunch-type growth habit.

Fine fescues can tolerate mowing heights that range widely from putting green heights to un-mowed. They are used as monocultures or in mixtures with other grasses for golf course putting green, fairway, and rough turfs as well as home lawns (Newell and Gooding 1990; Dernoeden et al., 1994; Bonos and Huff, 2003). Fine fescues require less water and nitrogen (N) fertilizer to maintain an acceptable turf cover compare to other cool-season turf species such as Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L) (Ruemmele et al., 1995; Watkins, 2014). All fine fescue species were able to survive to a 60-day drought in Minnesota and Wisconsin when maintained at fairway mowing height; however, there was no clear pattern in the drought response differences among fine fescue species (Reiter et al., 2017). Dernoeden et al. (1994) reported better turf quality and less weed encroachment on hard fescue and sheep fescue than tall fescue with little or no irrigation, fertilizer, or herbicides in a three-year study. Bourgoin (1997) studied four fine fescue species under three levels of N (0, 60, and 120 kg ha^{-1} $year^{-1}$) and ranked N efficiency ratio among fine fescue species from greatest to least as follows: hard fescue > strong creeping red fescue > Chewings fescue > slender creeping red fescue Result also indicated a high annual N fertilization rate was not necessary for an acceptable turf quality with fine fescues (Bourgoin, 1997).

Fine fescues are also known for their ability to tolerate shade, drought, salt, and cold stresses, as well as their adaptation to infertile and acidic soils (Beard, 1973;

Dernoeden et al., 1994; Ruemmele et al., 1995; Meyer and Pedersen, 2000; Gardner and Taylor, 2002; Friell et al., 2015; Reiter et al., 2017). In general, *F. rubra* ssp. are more tolerant to lower mowing heights and drought stress than *F. ovina* ssp. (Minner and Butler, 1985). Chewings fescue has the best shade tolerance, followed by slender creeping red fescue, strong creeping red fescue, hard fescue and lastly, sheep fescue (van Huylenbroeck et al., 1999; Gardner and Taylor, 2002). Fine fescues have a broad range of tolerance to salt; slender creeping red fescue has the best salt tolerance among five species while hard fescue and sheep fescue are most sensitive to the high concentration of salt (Ahti et al., 1980; 2001; Zhang et al., 2013).

Major diseases for fine fescues include, but not limited to, summer patch (caused by *Magnaportheopsis poae* Landschoot and N.Jackson), red thread [caused by *Laetisaria fuciformis* (McAlpine) Burds.], pink snow molds [*Microdochium nivale* (Fr.) Samuels and I. C. Hallet], gray snow mold (*Typhula incarnata* Fr.), leaf spot (caused by *Bipolaris* spp.), and dollar spot [*Clarireedia* ssp. (F.T. Bennet) Beirn, Clarke, and Crouch]. Susceptibility among fine fescues to these diseases varies; however, no single species of the five fine fescues are resistant to all the major diseases. Strong creeping red fescue, slender creeping red fescue, and hard can be severely damaged by summer patch (Han et al., 2003). Strong creeping red fescue is also more susceptible to dollar spot, red thread and leaf spot diseases than Chewings fescue and hard fescue (Shortell et al., 2005). Hard fescue exhibited the greatest resistance to both pink snow mold and gray snow mold while the Chewings fescue is the most susceptible species; strong creeping red fescue and slender creeping red fescue had intermediate levels of resistance (Watkins, 2017).

Lack of traffic tolerance is a major weakness of fine fescues. Fine fescues have been considered less traffic tolerant than other turf species (Shearman and Beard, 1975b; Minner et al., 2005). However, recent studies indicated that improved cultivars of fine fescue could provide acceptable turf cover under traffic stress with reduced maintenance (Horgan, 2007; Watkins et al., 2010; Cortese et al., 2011). The low-input characteristics of fine fescues provide options to the turf industry as the regulations of pesticide and water use on turfgrass landscapes become stricter. More research is needed to improve the traffic tolerance and disease resistance of fine fescues to increase the use of fine fescue at low-input sites (Ruemmele et al., 2003; Bonos and Huff, 2013).

TRAFFIC

Traffic tolerance and recuperative ability are important attributes of turfgrass that govern the durability of frequently used recreational and sports turf, golf courses, cemeteries, and home lawns. Traffic is a source of abiotic stress that can produce four types of damage: wear, soil compaction, rutting or soil displacement, and divoting (Beard, 1973; Carrow and Petrovic, 1992). Wear injury directly affects aboveground plant parts via tearing, bruising, and shredding of leaf tissue resulting from horizontal forces (Beard et al., 1974; Shearman, 1988; Vanini et al., 2007). Soil compaction results in an increase in soil bulk density and a decrease of soil porosity, which can lead to adverse soil conditions such as low soil oxygen, and low water infiltration (Carrow and Petrovic, 1992). Soil displacement (rutting) is the compression and physical movement of soil caused by foot and vehicular traffic, especially under wet conditions. Soil displacement can scuff or tear plant parts and damage the turfgrass crown as well as the upper regions of the root system (Harivandi, 2002). Divoting is one of the most acute and destructive forms of traffic, which occurs when pieces of the turf are torn or chopped loose during the game of horse racing, polo, golf, or sports with aggressive foot action (Murphy and Ebdon, 2013).

The ability of turfgrass to withhold and recover from traffic stresses could be affected by numerous factors, including the form of traffic, season of traffic application, soil and rootzone type, soil water content, and the regime of maintenance practices. In the following sections, the effect of traffic form and traffic season will be discussed.

Traffic Simulator

Wear and soil compaction, either separately or in combination, have been the most extensively studiedcomponent of traffic (Murphy and Ebdon, 2013). Various simulators have been constructed to impart both wear and soil compaction on turf plots. Differential-Slip (D.S.1), described by Canaway (1976), is a self-propelled machine that applies both vertical and horizontal forces to the turf. The Brinkman Traffic Simulator (BTS), towed by a vehicle during operation, has two studded rollers rotating at different speeds while pressing and shearing the turf surface (Cockerham and Brinkman, 1989). Similar machines, including the Georgia Soil Compaction Wear (GA-SCW) traffic simulator and the Nebraska Soil Compaction Wear (NE-SCW) traffic simulator, were developed by Carrow et al. (2001) and Shearman et al. (2001), respectively. More recently, the Cady Traffic Simulator (CTS), a modified walk-behind core cultivation unit equipped with cleated ‘feet’, was developed to impart the trampling form of traffic (Henderson et al., 2005).

Simulators were developed to study wear stress by producing primarily wear with minimal impact of soil compaction. In early studies, Perry (1958) described a lightweight wheeled unit designed to travels in a circle around a vertical axis, which was utilized by Youngner (1961) to produce a scuffing abrasive type of wear on turf plots. A similar sled device was developed by Shearman (1974) to mimic wear stress caused by golf carts and maintenance equipment. Canaway (1982) modified the D.S.1 (Canaway, 1976) device with golf-shoe spikes and rubber surfaced rotor to simulate golf spikes injury and abrasion. More recently, Shearman et al. (2001) described the GA-W traffic simulator, a self-propelled unit with a rubber-coated roller to apply wear stress with some soil compaction in long-term studies. The Rutgers Wear Simulator (RWS) is a machine equipped with rubber paddles on a rotating axle to primarily apply abrasive wear on the aboveground plant parts with minimal soil compaction (Bonos et al., 2001).

Studies were conducted to compare different simulators and associate artificial damage to actual athletic events. Canaway (1981a) reported that the damage caused by two passes of D.S.1 per week was similar to the midfield area of a pitch during a soccer game. Cockerham and Brinkman (1981) indicated two passes of BTS was approximately equivalent to the area of greatest traffic concentration during an American football game based on the calculation of cleat dents per square foot. Vanini et al. (2007) compared the effect of CTS and BTS on soil physical properties and concluded that two passes with CTS produced traffic stress similar to 10 passes with BTS.

Form of Traffic

Abrasive wear and soil compaction may occur simultaneously on a site. The development of traffic simulators facilitated the research to evaluate the performance of turf plots under wear and soil compaction either separately or in combination. Carrow (1980) indicated that wear stress might often be the primary factor contributing to differences among turfgrass species than soil compaction. Carrow and Petrovic (1992) also pointed out that wear is expected to be the dominating stress on sandy rootzones with limited soil moisture; while soil compaction dominates on fine-textured soils with high moisture content

Research has been conducted to differentiate between the effect of wear and soil compaction on turfgrass stress. A study on a sand-based putting green with creeping (*Agrostis stolonifera* L.) and velvet (*Agrostis canina* L.) bentgrass indicated that wear stress was more detrimental than soil compaction to turf performance and soil physical properties (Cashel et al. 2005). A similar result was observed by Samaranayake et al. (2008) on creeping bentgrass cultivars grown on a sandy loam putting green and a sandy loam fairway. Dest et al. (2010) also suggested wear stress being the major source of damage, which accounted for 90% of the total treatment variation in the injury of Kentucky bluegrass and perennial ryegrass mixture turf. They also noted that sand rootzone is less prone to soil compaction than silt loam as greater rooting of grasses was associated with sand-based rootzone. Dest et al. (2017) reported similar results indicating wear contributed approximately 80% of the total variation in the injury of Kentucky bluegrass sod.

The development of RWS (Bonos et al., 2001) allows the operators to evenly impart abrasive wear to undulated turf surfaces as other simulators with rigid rollers may impart greater wear stress to the high spots and leave the lower area with less damage (Murphy and Ebdon, 2013). Park et al. (2011) compared the effect of trampling stress

(CTS; Henderson et al., 2005) versus wear stress (RWS; Bonos et al., 2001) and reported that wear stress caused more injury and was more effective at distinguishing the traffic tolerance of Kentucky bluegrass cultivars. In a different study, Park and colleagues (2014) observed greater damage and longer recovery periods after treated with RWS compared to CTS and BTS on Kentucky bluegrass, perennial ryegrass, and tall fescue. Grimshaw et al. (2018) indicated the use of RWS could reduce variations involved with the selection and may increase selecting efficiency as compared to simulators, which imparts both aspects of traffic.

Although wear was the predominate form of traffic compared to soil compaction in many studies, it is important to be aware of the association between wear and soil compaction. Accumulation of organic matter serves as a cushion to absorb and reduce the magnitude of compacting forces. On the other hand, deterioration of turf cover under intensive wear eventually increases the vulnerability of the soil to be compacted. Samaranayake et al. (2008) suggested the accumulation of organic matter (verdure, thatch, and mat) in turfgrass limited the soil compaction. Cashel et al. (2005) also noted that grass grown on a sand-based rootzone is relatively tolerant of intense rolling (compaction) as long as turf density is not reduced. More research is needed to assess the relative importance of wear and soil compaction.

Season Effect on Traffic Tolerance

Environmental factors include climate, soil, and pest incident that may interact and alter the performance of turfgrass under wear stress. Bonos et al. (2001) noted the importance of identifying the environmental factors causing different traffic response of turf species to improve the selection efficiency.

Wear tolerance was found positively correlated to turf quality and shoot density in many studies (Trenholm et al., 2000; Bonos et al., 2001; Cashel et al., 2005; Samaranayake et al., 2008; Park et al., 2009). Trenholm et al. (2000) suggested that a positive correlation between increased shoot density and wear tolerance could be a result of a greater quantity of tissue available to absorb the impact of the injury. The response of turfgrass to traffic can vary by season due to the significant effect of season on turf quality and density.

In general, cool-season (C3) species, due to their less efficient photosynthetic pathway, are more vulnerable to heat and drought stress than warm-season (C4) turfgrass species. During drought stress, the deterioration of cool-season grasses can be accelerated, and the detrimental effects of traffic can be more noticeable compared to warm-season grasses (Braun, 2017). Park et al. (2010) observed more severe damage, and greater difference among Kentucky bluegrass cultivars under wear stress applied during summer and autumn than spring. Besides, the performance of some Kentucky bluegrass cultivars under wear stress was compromised by greater susceptibility to disease. The author also noted that the ability of disease-susceptible cultivars to perform well under traffic stress is limited to the season when the disease pressure is low.

In summary, the seasonal effect can be significant in the traffic tolerance of turf species and cultivars. It is important to investigate traffic tolerance in different seasons to identify broadly adapted cultivars with improved traffic tolerance.

Traffic Research on Fine Fescues

Durability and persistence under traffic stress is an important attribute of turfgrasses. Fine fescues are not utilized to the same extent as other cool-season turfgrass species partly due to their lower tolerance of traffic and slower recuperative ability after damage. A survey conducted on consumers in the U.S. and Canada suggested that traffic tolerance is one of the most important attributes when selecting grass species (Yue et al., 2017). Thus, improvement in the traffic tolerance of fine fescues can improve the utilization of fine fescues by the turf industry.

Interspecific level trials indicate inferior traffic tolerance of fine fescues compared to other cool-season grass species. Shearman and Beard (1975b) reported that ‘Cascade’ Chewings fescue was severely injured and ranked the lowest among seven cool-season species tested under both sled (foot-like) and wheel (vehicular) wear stress. ‘Highland’ Chewings fescue and ‘Highlight’ strong creeping red fescue were intolerant of wear and very susceptible to invasion by annual bluegrass when trafficked with D.S.1 (Canaway, 1981b). Minner and Valverde (2005) also reported that ‘Cindy’ strong creeping red fescue had more exposed soil and invasive weeds than all other turfgrass species under traffic applied with GA-SCW (Carrow et al., 2001). Cereti et al. (2010) compared the traffic tolerance of Chweings fescue, strong creeping red fescue, and slender creeping red fescue to other cool-season grasses; fine fescue species as a group had the lowest turf quality under traffic stress compare to Kentucky bluegrass, tall fescue, and perennial ryegrass. The authors suggested the poor wear tolerance of fine fescue was due to the impact of high temperatures of the Mediterranean climate in central Italy.

Traffic tolerance among fine fescue species evaluated by Shildrick during the 1970s indicated that Chewings fescue and slender creeping red fescue were more wear tolerant than strong creeping red fescue () in monocultures and mixtures with perennial ryegrass (Shildrick, 1975; Shildrick, 1976a, 1976b, 1976c; Shildrick 1977; Shildrick et al., 1983). A more recent study conducted by Bonos et al. (2001) indicated better wear tolerance with Chewings fescue and hard fescue than strong creeping red fescue, slender creeping red fescue, and sheep fescue. Watkins et al. (2012) reported better traffic tolerance and recovery of hard fescue than Chewings fescue and sheep fescue under golf cart traffic simulation.

There is a growing need to wear tolerant grass under reduced maintenance inputs (Murphy and Ebdon, 2013). Improved traffic tolerance of newer fine fescue cultivars was reported under reduced maintenance on golf course fairways, tennis courts and cricket squares (Horgan et al., 2007; Cortese et al. 2011; Cross et al., 2013). Fairway trials in the North Central US region indicated that fine fescues and colonial bentgrass mixtures exhibited good turf quality under proper management (Horgan et al., 2007). Mono-stands of Chewings fescue and strong creeping red fescue cultivars also provided acceptable turf cover under traffic stress with reduced management regime (Stier, 2012; Newell and Wood, 2003; Horgan et al., 2007; Watkins et al., 2010; Watkins et al., 2012). Some slender creeping red fescue cultivars were also identified as having superior wear tolerance, in both mixtures and monocultures, under wear stress simulating a tennis court (Newell et al., 1996) and cricket square (Newell and Wood, 2005). Cortese et al. (2011) investigated wear tolerance of fine fescues under extremely low-maintenance situations (no irrigation after establishment) and concluded that hard fescue and Chewings fescue have the best wear tolerance and recovery among all fine fescue species. A similar result was observed by Cross et al. (2013).

Improvements in turfgrass traffic tolerance can be achieved if sufficient heritable variations are available for plant breeders to exploit during the development of new cultivars. Grimshaw et al. (2017) used different simulators to evaluate the heritability of wear and traffic tolerance in Chewings fescue, strong creeping red fescue, and hard fescue. The author indicated the use of RWS to impart only wear stress improved the screening efficiency compared to a simulator imparting both wear and soil compaction due to the added environmental variation. Among the species tested, hard fescue demonstrated the best wear and traffic tolerance followed by Chewings fescue and strong creeping red fescue. The author concluded that improvement of wear and traffic tolerance in fine fescues is possible through recurrent breeding methods based on the selection of replicated clonally propagated genotypes.

In summary, among all the fine fescues species, hard fescue and Chewings fescue are often the top performer under traffic stress among fine fescues (Shildrick, 1976a, 1976b, 1976c; Bonos et al., 2001; Newell and Wood, 2003; Cereti et al., 2010; Watkins et al., 2010, 2012). Due to the breeding efforts across all fine fescues, recent studies showed improvements in traffic tolerance of strong creeping red fescue and slender creeping red fescue(Newell and Wood, 2003; Watkins et al., 2010; Cross et al., 2013; Grimshaw et al., 2018). There are well-documented differences in wear and traffic tolerance among cultivars within each fine fescue species. Continued focus on improving traffic tolerance of fine fescues should help to expand the use of these low-maintenance species.

PLANT CELL WALL

Plant cell walls play important roles in several essential functions, including providing support for the plants, intercellular communication, and plant-microbe interaction (Keegstra, 2010). They are the first defense against many environmental stresses such as temperature change, water, and nutrient deficiency and potential pathogen invasion (Taiz and Zeiger, 2002). Plant cell walls are usually divided into two categories: primary walls and secondary cell walls. Primary cell walls are the walls that surround growing cells or cells capable of growth (Scheller and Ulvskov, 2010). After cessation of cell expansion, some cells, such as vessel elements or fiber cells, develop a secondary wall, which is comprised of thickened structures containing lignin (Keegstra, 2010).

Plant cell walls are mostly composed of polysaccharides, proteins and phenolic compounds (lignin). Classically, cell wall polysaccharides have been grouped into cellulose, hemicelluloses, and lignin (Scheller and Ulvskov, 2010). Cellulose is the single most abundant component in plant cell walls, which is highly stable and insoluble in water. Cellulose is the only well-defined class which consists of a collection of β-1,4-linked glucan chains that interact with each other via hydrogen bonds to form a crystalline microfibril (Keegstra, 2010). Hemicellulose is amorphous and soluble in alkaline or acid solutions, which comprise a diverse class of polysaccharides, including xylans, xyloglucans, glucomannans, and mixed-linkage glucan. Hemicellulose assists the cellulose in forming cellulose-hemicellulose networks with greater inaccessibility (Aman, 1993). Lignin is a polymer composed of phenylpropanoid monolignol units, which are necessary to impart strength and rigidity to plant cell walls and provides mechanical support for aerial shoots and plant resistance to diseases, insects, cold temperatures, and other stresses (Rhodes, 1985).

Cell wall constituents, including cellulose, hemicellulose and lignin, can be determined on a dry weight basis (g kg^{-1}) using the fiber analysis outlined by Goering and Van Soest (1970). This method has gained wide acceptance in determining the concentration of cell wall constituents and has been used in many turfgrass studies (Shearman and Beard, 1975b; Bourgoun et al. 1985; Trenholm et al. 2000; Brosnan et al., 2005; Dowgiewicz et al., 2011). The neutral detergent fiber (NDF) is the most common measure of total cell wall content which covers most of the structural components. The NDF method is based on the extraction of the sample with a hot neutral solution of sodium lauryl sulfate (Goering and Van Soest, 1970). The acid detergent fiber (ADF), on the other hand, measures the insoluble fiber within a plant cell (cellulose and lignin). The ADF method uses heat treatment of a sample with 0.5 M sulfuric acid containing cetyltrimethylammonium bromide to dissolve hemicellulose and soluble minerals and determine the concentration of lignocellulose, which contains cellulose and lignin (Goering and Van Soest, 1970). The weight difference between NDF and ADF gives a concentration estimate of hemicellulose. The modified acid detergent (MAD) comprises cellulose, hemicellulose, and lignin, described by MAFF (1981), which was also used in turfgrass studies (Cnanway, 1978; Cnanway, 1981b; Kilmartin, 1994). The acid detergent lignin (ADL) method uses 72% sulfuric to dissolve cellulose after the ADF procedure, and the residuals determine the concentration of lignin (Goering and Van Soest1970). The weight difference between ADF and ADL gives a concentration estimate of the cellulose concentration. Jung (2012) noted that ADF could dissolve a small amount of lignin before the ADL procedure, which might result in a concentration underestimate of lignin (ADL), and concentration overestimates of hemicellulose (NDF-ADF) and cellulose (ADF-ADL). In spite of its limitation, the Goering and Van Soest method (1970) has been the most widely used method to determine the concentration of cell wall constituents.

Cell Wall Constituents and Traffic Tolerance

Turfgrasses are different than other crops as they can form and maintain ground cover under regular mowing and traffic. Studies have indicated correlationsbetween cell wall constituents and traffic tolerance of turfgrass. This section is aimed to review and discuss the correlations between cell wall contents and traffic tolerance.

Positive correlations between traffic tolerance and concentrations of cell wall constituents have been reported at the inter-specific level (Shearman and Beard, 1975b; Canaway, 1978). As the pioneers assessing the correlations between concentrations of cell wall constituents and wear tolerance, Shearman and Beard (1975 a, b, c) found that visual wear assessment (1 to 5; 1=no injury, 5=bare soil) was highly correlated with three parameters: total cell wall content (TCW) remaining expressed on a weight per unit area basis (r=0.98), percentage verdure (r=0.97), and percentage chlorophyll (r=0.97) on a weight per unit area basis (Shearman and Beard, 1975a). The authors indicated that the combined effects of all cell wall constituents expressed on a weight per unit area basis (accounted for 97% of variation) and on a dry weight basis (accounted for 96% of variation) were the best criteria for selecting wear tolerance of turfgrass. They also suggested using TCW on a weight per unit area basis (accounted for 78% of variation) as a simple and rapid procedure for efficiently screening large numbers of selections (Shearman and Beard, 1975b). Canaway (1978) also reported positive correlations between wear tolerance and MAD fiber and cellulose. However, negative correlations were detected in a later study on the same turf species (Canaway, 1981). The author proposed using verdure biomass as a more reliable predictor for wear tolerance than MAD fiber or cellulose content due to the discrepancies of the two studies.

Studies investigating traffic tolerance and concentrations of cell wall constituents have also been conducted at the intra-specific level (Bourgoun et al. 1985; Brosnan et al., 2005; Den Haan et al., 2009; Dowgiewicz et al., 2011; Kilmartin, 1994; Trenholm et al. 2000; Roche et al., 2009). Bourgoin et al. (1985) reported no correlations between ADF fiber and wear tolerance of cultivars within fine fescue, perennial ryegrass, and Kentucky bluegrass. Kilmartin (1994) reported a weak positive correlation (r=0.68) between wear tolerance and the MAD fiber content of perennial ryegrass cultivars. Brosnan et al. (2005) observed that wear tolerance of Kentucky bluegrass cultivars was positively associated with concentrations of TCW (r=0.29 for the un-mowed spaced plant; r=0.37 for mowed turf) and lignocellulose (r=0.35 for the un-mowed spaced plant; r=0.32 for mowed turf). Roche et al. (2009) reported that wear tolerance of bermudagrass grass (*Cynodon dactylon* L.) and bermudagrass hybrids (*C. dactylon* L. x *C. transvaalensis* Burtt-Davy) were positively associated with the concentration of TCW, lignin, and hemicellulose. Similar results were reported on *Agrostis* cultivars, where greater concentrations of TCW, hemicellulose, and lignocellulose were found in cultivars with improved wear tolerance (Dowgieziwiz, 2009).

Negative correlations between the concentration of cell wall constituents and wear tolerance have also been reported (Den Haan et al., 2009; Trenholm et al., 2000). Trenholm et al. (2000) indicated that wear tolerance of seashore paspalum (*Paspalum* *vaginatum* Swartz.) was negatively associated with TCW concentration in both leaf and stem, whereas wear tolerance of bermudagrass hybrids was associated with reduced stem cellulose content and increased leaf lignin. A greenhouse study conducted by Den Haan et al. (2009) found that wear tolerant perennial ryegrass cultivars had a lower concentration of TCW and lignin but a higher protein content compared to wear intolerant cultivars.

It appears that relationships between cell wall constituents and tolerance to traffic vary with species. Thus, there is a need to develop screening protocols at the species-specific level to reliably select wear tolerant cultivars using the concentration of cell wall constituents as a predictor.

Factors Influence Cell Wall Composition of Grass

Units for Presenting Data on Constituents

The concentration of cell wall constituents can be presented on a dry weight basis (g kg^{-1}) or on a weight per unit area basis (g dm^{-2}) by multiplying the concentration of cell wall constituents (g kg^{-1}) with biomass (kg dm^{-2}). Shearman and Beard (1975b) indicated the concentration of TCW was significantly correlated ($r = 0.88$) to turfgrass wear tolerance when presented on a weight per unit area basis (g dm^{-2}) while a weaker correlation ($r = 0.33$) was found when presented on a dry weight basis (g kg^{-1}). Canaway (1981) also reported that wear tolerance of turfgrass was positively correlated with MAD fiber and cellulose expressed on a weight per unit area basis (g dm^{-2}) while negatively correlated with these constituents when expressed on a dry weight basis (g kg^{-1}). The author indicated that the ranking of the concentration of cell wall constituents largely followed the same pattern as for biomass when expressed on a weight per unit area basis (g dm^{-2}) due to the differences in biomass were much greater than the relatively small differences in concentration of cell wall constituents.

Leaf vs. Stem

All differentiated plant cells contain specialized cell walls; thus, cell wall composition varies between leaves and stems of grasses (Keegstra, 2010). In general, plant leaves are comprised of many thin-walled mesophyll cells, while plant stems are made up of mostly highly lignified xylem cells and structural tissues (Hacker and Minson, 1981; Nelson and Moser, 1994). Stems contain a higher proportion of thick-walled tissues (sclerenchyma, xylem fiber, and xylem vessel) and less photosynthetic tissues (mesophyll, chlorenchyma) than leaves, resulting in stems having a higher cell wall concentration than leaves. Stem lignin content is associated with secondary cell wall formation, and thickening, which often increases as plant tissues become more mature (Akin, 1989; Jung, 1989; Buxton and Russell, 1988). Numerous studies on cool-season forage grasses and legumes indicated that cell wall concentration is greater in stems than in leaves (Albrecht et al., 1987; Buxton and Brasche 1991; Buxton and Hornstein, 1986; Hodgson et al., 2010).)

In some warm-season C4 species, however, the cell wall concentration in leaves equals or exceeds that of stems. Warm-season C4 species have more compact vascular bundles and a distinct thick-walled parenchyma bundle sheath surrounding each bundle due to the Kranz leaf anatomy (Buxton and Casler, 1993). The leaves of cool-season C3 grass species have a greater proportion of loosely arranged mesophyll cells, which are usually the first to be digested (Akin, 1989). Warm-season C4 grass species have long been recognized for a greater concentration of structural polysaccharides compare to cool-season C3 grass species, (Bailey, 1973).

Nitrogen Fertilization

Mineral nutrients are critical for the proper establishment and management of turfgrasses, and they have a great impact on plant growth. Nitrogen (N) is by far the most researched nutrient applied to turfgrass (Frank and Guertal, 2013). However, there have been limited studies on N fertilization effect in altering cell wall composition in turfgrass.

Studies have indicated significant N fertilization effects on the chemical composition and palatability and digestibility of the forage grass; however, no consistent N effect was observed. Valk et al. (1996) reported no N fertilization effect on the concentration of cell wall constituents of forage type perennial ryegrass. Deinum and Dirven (1976) and Wilman and Wright (1978) reported a decrease in the concentration of cell wall constituents with an increasing N rate of Congo grass (*Brachiaria ruziziensis*) and African bristlegrass (*Setaria sphacelate*). Wilman and Wright (1978) also indicated a reduced concentration of cell wall constituents with increased N rate on Italian ryegrass (*Festuca perennis*), perennial ryegrass, and cocksfoot (*Dactylis glomerata L.*). However, an opposite trend was observed on the same grass species by Behaeghe and Carlier (1973). A more recent study conducted by Hodgson et al. (2010) investigated the cell wall composition of *Miscanthus* at different levels of N (0, 50, 100, 150, 200, or 250 kg ha^{-1}). The result indicated increasing N rate significantly decreased the concentration of cell wall constituents in both stem and leaf tissues of *Miscanthus*. However, Allison et al. (2012) reported an opposite result: increasing level of N (0, 100, 150 or 250 kg ha^{-1}) resulted in a small but statistically significant increase of TCW, cellulose and lignin concentrations of switchgrass (*Phalaris virgatum*) and reed canary grass (*Phalaris arundinacea*). In turf research, Shearman and Beard (1975d) observed improved wear tolerance of creeping bentgrass with increased N and K application. They also reported increased concentrations of TCW, lignocellulose, cellulose, and lignin content with increasing N rate.

Wilman et al. (1977) suggested that the variation in cell wall content resulting from N fertilization was greater for earlier regrowth stages of forage grass, and the effect disappeared almost completely after six to eight weeks of regrowth. They indicated that N fertilization promotes the growth of new succulent tissues, and results in a decrease of cell wall concentration at an early regrowth stage.

Maturity Stage

Jung (2012) noted that the plant maturation process was the greatest single factor that affects cell wall composition. The concentration of cell wall constituents increases during maturation as a thicker secondary cell wall formed, and plant cells become more lignified (Morrison, 1980; Albrecht et al., 1987). Shearman and Beard (1975b) monitored the changes of cell wall constituents of seven turf species in the growth chamber during the first ten-week after seedling emergence. They noted a trend of an increasing concentration of TCW as seedlings matured. Wilson and Kennedy (1996) suggested that the increased concentration of cell wall constituents with maturity primarily resulted from a decrease in the leaf-to-stem ratio in forage grass.

Environmental Factors

Environmental stresses, including extreme temperature, water deficit, and shade, could affect the physiological and morphological adaptation of grasses (Buxton and Casler, 1993).

Increasing temperatures often cause rapid conversion of soluble carbohydrates into structural polysaccharides; thus, forage grown at high temperatures generally have a higher concentration of cell wall components than forages grown at low temperatures (Buxton and Casler, 1993). Sullivan (1956) reported a positive correlation between lignin synthesis and temperature for eight cool-season grass species. Several studies confirmed that the concentration of TCW, hemicellulose, and cellulose increases with increasing growth temperature in forage grass (Moir et al., 1977; Henderson and Robinson, 1982; Fales, 1986). In turf research, Shearman and Beard (1975b) found that TCW increased significantly during summer (July to September) but declined during autumn (October); however, the relative ranking of TCW concentration among species was consistent across seasons.

Drought stress often occurs with high temperature and results in lower cell wall concentration compared to non-stressed forage. Halim et al. (l989a) reported that the concentration of cell wall constituents in both leaves and stems of alfalfa decreased with increasing severity of drought stress. Wilson (1982) attributed the influence of drought stress to slow growth rate and delay of stem development, which results in leafier plants with low cell wall concentration.

Buxton and Casler (1993) suggested that environmental factors can indirectly affect the cell wall composition of forage grass by altering the leaf-to-stem ratio. High growth temperature promotes stem development over leaf development, which results in a lower leaf-to-stem ratio and a higher concentration of cell wall constituents (Deinum, 1984).

NEAR-INFRARED REFLECTANCE SPECTROSCOPY

The English astronomer Sir William Herschel first discovered near-infrared electromagnetic radiation at the beginning of the 19th century. Herschel (1800) used a glass prism to separate sunlight and detected a rising of temperature below the red end of the spectrum, which was later named infrared. Norris et al. (1976) pioneered the application of near-infrared reflectance spectroscopy (NIRS) to the analysis of agricultural products. Subsequently, NIRS has been widely adopted for the rapid determination of organic components as improvements in instruments and mathematical tools employed to extract and process analytical information from the spectral data has occurred. Paquini (2018) reviewed NIRS research and indicated that there are three sustaining pillars of the modern NIRS technology: fundamentals of vibrational spectroscopy, instrumentation, and chemometrics. This section intends to summarize: i) the fundamentals of near-infrared reflectance spectroscopy (NIRS); ii) calibration and validation of NIRS; iii) application of NIRS to agricultural products.

Fundamentals of NIRS

Near-infrared reflectance spectroscopy (NIRS) acquire qualitative and quantitative information from a sample via interaction of near-infrared electromagnetic radiation (700- to 2500-nm) with chemical bonds. The absorbance of radiation in liquid samples is often measured by transmittance, while diffusive reflectance is often used as a non-destructive and direct analysis of solid samples to extract useful analytical information (Shenk et al., 1992).

The absorption in the NIR region is mainly due to the vibration of covalent bonds in different forms. Molecular vibrations can occur as hydrogenic stretching (a change in the length of a bond), bending (a change in the angle between two bonds), or deformation vibration in the form of X-H, where X can be carbon (C), nitrogen (N), oxygen (O) or sulfur (S). Other important functionalities in the NIR region include vibrations of strong chemical bonds between heavier atoms, such as carbon-to-oxygen (C=O) double-bond stretching, carbon-to-carbon (C=C) stretching vibrations, and metal halides.

Based on Beer's Law, the absorbance of a homogeneous sample containing an absorbing substance is linearly proportional to the concentration of the chemical bonds (Shenk and Westerhaus, 1994). The NIR spectrum contains information about the chemical bonds in the sample, which is the summation of the major chemical and physical properties of the sample. A NIRS calibration model develops a mathematical relationship between the spectral absorbance and the properties of interest.

Development of NIRS Equation

Numerous studies have demonstrated the analytical versatility and usefulness of NIRS as a non-destructive, rapid, and precise technique. Pasquini (2018) reviewed the recent development of NIR spectroscopy and summarized scientific literature dedicated to specific fields. In a NIRS spectrum, the various constituents of the sample have some overlapping peaks; thus, proper calibration of a NIRS model is needed to extract the desired information (Gislum 2004).

The establishment of a NIRS model consists of three steps: (1) preprocessing of NIR spectral data; (2) calibration; (3) validation and optimization.

Preprocessing of Spectra

The particle size, texture, and packing density of samples can affect the absorbance of NIR radiation. Variances in spectral data from sources other than the properties of interest could introduce noise and disturb the calibration process (Cao, 2013). Multiplicative signal correction (MSC) and standard normal variate (SNV) are the transformations often employed to minimize spectral variability associated with changes in the particle size of samples. Other preprocessing techniques for NIRS data have been critically evaluated (Rinnan et al., 2009).

Detection of outliers is important to ensure the accuracy and precision of a regression model. The Mahalanobis distance (H statistic) is the most widely employed measurement to detect outliers based on the spectral information (De Maesschalck 2000). The Mahalanobis distance determines whether a sample falls within a given region of multidimensional space. A small distance indicates that the sample is "close to" the center of the region, and thus within it. Principal component analysis (PCA) is often used to compress information from numerous wavelengths into a few independent components and to compute a general Mahalanobis distance (Fujikoshi et al., 2011). The Mahalanobis distance can be calculated from the matrix equation described by ASTM practice (ASTM International, 2016). Another criterion often used to detect spectral outlier is the Hoteling statistics (t^2). The t^2 statistics are highly effective in selecting outliers for large data sets, where a normal distribution of score values is probable. The calculation of Hoteling statistics (t^2) is described by ASTM practice (ASTM International, 2017).

It is important to note that outliers can either display a very different spectrum or may have an incorrect property value attributed to the reference analytical laboratory (Pasquni, 2018). Although samples with extreme spectral data are often considered as outliers, these may be merely underrepresented in the data set. Pasquini (2018) suggested that outliers should not be simply removed from the data sets before the reasons why the outliers were present were verified. The practice can help to increase the knowledge about the data set and provide information on how to improve its quality to achieve better model performance.

Calibration

Spectral data and reference data (chemical or physical properties of interest) are two major components for the development of a NIRS calibration model. Samples with complex composition must be analyzed using accepted or authorized chemical procedures to produce reference data before calibration. Workman (2008) suggested using the average composition as determined by replicate chemical measurements for each sample to reduce the random error in reference data, which cannot be removed mathematically.

García-Sánchez et al. (2017) suggested that 20 to 200 samples are necessary to develop a multivariate calibration equation depending on the complexity of the samples. Williams (2007) proposed two main techniques to perform sample selection for the calibration set, the conventional method, and the spectral method. The conventional method accumulates samples until the reference analyses cover the entire constituent range. The drawback of the conventional method is that a great number of samples need to be analyzed to be able to select a sample set with uniform distribution. The conventional method is the preferred method for selecting calibration sets for agricultural products with complicated substances, such as oil, protein and cellulosic component (Williams, 2007). The spectral method, however, selects samples strictly based on their spectral characteristics. Reference analyses only performed on a relatively small number of selected samples that display the most comprehensive variance in spectral data. The spectral method selects a reduced set of evenly distributed samples, which avoids redundancy and minimizes the cost of analyzing samples using chemical procedures. However, the spectral method for selecting a sample calibration sets can be challenging when attempting to determine minor constituents with small variance in spectral data (Williams, 2007).

Multiple linear regression (MLR) is a general statistical technique used to develop NIRS calibration model after sample selection (Mark, 2001; Workman, 2008). This technique eliminates wavelengths that are not contributing to improving the performance of a model and produce robust and stable regression coefficients without the usual problems associated with highly collinear variables. However, the negative aspect of working with a reduced set of wavelengths is the loss of the ability to identify outliers, which makes the model prone to unnoticeable interferences in prediction samples (Pasquni, 2018).

Unlike MLR, partial least squares regression (PLS; Bjørsvik and Martens, 1992) requires no wavelength removal. The PLS regression method collects the most useful information from all wavelengths and combines them into PLS factors (Workman, 2008). This method continues to be the most commonly used multivariate analysis technique due to its faster convergence to the optimum prediction performance, using a lower number of latent variables (Wentzell, 2003). The PLS assumes a linear relationship of the reference data as a function of the spectral variations; however, weak non-linearities can also be adjusted by increasing the number of latent variables (Pascuni, 2018). Workman (2007) summarized the advantages and disadvantages of a variety of calibration modeling techniques. The mathematical technique detail of the PLS can be found in ASTM E1655-17 (2012).

Validation and Optimization

According to ASTM International (2017), various statistics can be used to evaluate and optimize the performance of a NIRS calibration model. These statistics include, but are not limited to, coefficient of correlation (R^2), root mean square error of prediction (RMSEP), square error of prediction (SEP), bias and residual prediction deviation (RPD).

The determination coefficient (R_{pre}^2) of calibration is normally the first statistic used to evaluate a calibration due to its simplicity. R_{pre}^2 can be calculated as:

$$R_{pre}^2=1-\frac{\sum_{i=1}^{n}(Y_{P,i}-Y_{R,i})^2}{\sum_{i=1}^{n}(Y_{R,i}-\bar{Y}_R)^2}$$

where n is the number of unknown samples in the validation set; $Y_{P,i}$ is the NIRS predicted value; $Y_{R,i}$ is the reference value; $\bar{Y}_R$ is the mean of the reference values.

The formula to compute root mean square error of prediction (RMSEP), square error of prediction (SEP), Bias, and Residual prediction deviation (RPD) are:

$$RMSEP=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_{P,i}-Y_{R,i})^2}$$

$$SEP=\sqrt{\frac{\sum_{i=1}^{n}(Y_{P,i}-Y_{R,i})^2-\frac{\sum_{i=1}^{n}(Y_{P,i}-Y_{R,i})^2}{n}}{n-1}}$$

$$Bias=\frac{1}{n}\sum_{i=1}^{n}(Y_{P,i}-Y_{R,i})$$

$$SD=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_{R,i}-\bar{Y}_R)}$$

$$RPD=\frac{SD}{SEP}$$

where n is the number of unknown samples in the validation, $Y_{P,i}$ is the NIRS predicted value and $Y_{R,i}$ is the reference value, and $\bar{Y}_R$ is the mean of the reference values.

During calibration using PLS regression, it is critical to determine the optimal number of PLS factors to retain in the calibration model. Too few factors may leave important information unmodeled, while too many factors may introduce measurement noise from both spectral and reference data into the calibration model. Cross-validation (leave-one-out) is performed within the calibration sample set to optimize the model by selecting the appropriate number of PLS factors (Bjørsvik and Martens, 1992). Root means square error of cross-validation (RMSECV) can then be calculated to determine the optimal number of PLS factors needed to build the model:

$$RMSECV=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_{P,i}-Y_{R,i})^2}$$

where n is the number of samples used to calculate the model, $Y_{R,i}$ is the reference value of the omitted sample, and $Y_{P,i}$ is the predicted value of the omitted sample.

García-Sánchez et al. (2017), suggested a R_{pre}^2 value of 0.75–1.0 as an acceptable correlation for quantitative analysis and calibrations with a R_{pre}^2 value of 0.3-0.75 may be useful for qualitative analysis. Malley et al. (2003) proposed a guideline for evaluating model quality for environmental samples, including soil, sediments, animal manure, and compost, based on the R_{pre}^2 and the RPD. Excellent calibrations are with $R_{pre}^2 > 0.95$ and RPD > 4; successful calibrations are with $R_{pre}^2 = 0.9–0.95$ and RPD = 3–4; moderately successful calibrations are with $R_{pre}^2 = 0.8–0.9$ and RPD = 2.25–3; moderately useful ones have $R_{pre}^2 = 0.7–0.8$ and RPD = 1.75–2.25. Vrious other statistics can be used in the evaluation, selection, and validation of the calibration equations (Workman 2008; ASTM E1655-17, 2012; ASTM E1790-04, 2016; García-Sánchez et al., 2017).

Application of NIRS to Agricultural Products

The main constituents in agricultural products determined by NIRS are the total protein and protein fractions, soluble and structural carbohydrates, and digestibility of the forage (García-Sánchez et al., 2017).

Models for protein prediction

Volkers et al. (2003) established NIRS models based on 398 maize plants (*Zea mays*) to predict the crude protein of leaf and stem ($R_{pre}^2 = 0.96$ for leaf and $R_{pre}^2 = 0.99$ for stem). Hermida et al. (2005) developed NIRS models based on 144 samples of grass silage to determine the total nitrogen (TN), soluble nitrogen (SN), non-protein nitrogen (NPN), and acid detergent insoluble nitrogen (ADIN), with R_{pre}^2 values being 0.94, 0.92, 0.90, and 0.48, respectively. The author indicated that NIRS is not an effective method for quantitative analysis of ADIN in silage, which might due to the low sensitivity of NIRS to the bond of protein with acid-detergent fiber and the poor repeatability of the reference method. Similar results were reported by Nie et al. (2008), who developed NIRS models based on 230 alfalfa samples to predict the total crude protein (CP), true crude protein (TCP), neutral detergent insoluble protein (NDFCP), and acid detergent insoluble protein (ADFCP). The validation sample sets indicated an accurate and precise prediction for CP (R_{pre}^2=0.96) and TCP (R_{pre}^2=0.91). However, the prediction was less precise for NDFCP (R_{pre}^2=0.83) and ADFCP (R_{pre}^2=0.75). Ferreira et al. (2012) and Wang et al. (2014) established models to determine lipids, total protein and carbohydrate contents in soybean [*Glycine max* (L.) Merril] and fava beans (*Vicia faba* L.), respectively; the best calibration models were developed for protein (R_{pre}^2=0.81) and moisture (R_{pre}^2=0.80) estimation. Wang et al. (2014) analyzed 240 fava beans samples and observed superior model fitting for ground seed powder samples compared with samples of intact seed. The optimal models were based on seed powders for protein, starch, and total polyphenol with R_{pre}^2 values being 0.97, 0.93 and 0.89, respectively. They also reported a significant geographical factor (longitude, latitude, and altitude) effect on the nutritional composition of the fava bean.

Cell wall constituents prediction

Characterization of structural carbohydrates by NIR are well studied and extensively used with success in agricultural products (Norris et al., 1976; Abrams et al., 1986; Bruno-Soares et al., 1998; Nousiainen et al. 2003; Cozzolino et al., 2006; Fassio et al., 2009). Norris et al. (1976) developed a NIRS equation based on 87 samples of ground dry forages to predict crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), lignin (L) and in vitro dry matter disappearance (IVDMD), as well as in vivo digestibility (DMD), dry matter intake (DMI) and digestible energy intake (DEI). The author reported high R_{pre}^2 for CP (0.99), NDF (0.98), ADF (0.96), L (0.96), for IVDMD (0.95), DMD (0.88), DMI (0.80) and DEI (0.85) were reported. Nousiainen et al. (2003) established calibration models based on 94 silage grass samples using PLS to predict NDF, indigestible neutral detergent fiber (INDF), and digestible neutral detergent fiber (DNDF). The proportion of variance accounted for by the PLS calibrations was relatively high for NDF ($R_{pre}^2 = 0.96$) and INDF ($R_{pre}^2 = 0.95$) and slightly lower for DNDF ($R_{pre}^2 = 0.88$). These studies indicate a great potential of NIRS to predict the concentration of cell wall constituents.

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CHAPTER 2 Comparing Abrasive Wear and Cleated Traffic for Evaluating Fine Fescue Traffic Tolerance

ABSTRACT

The performance of fine fescues (*Festuca* spp.) may differ by the form of traffic stress; thus, the form of traffic may affect the screening efficiency during studies of traffic tolerance. The objective of this study was to evaluate the effect of abrasive wear and cleated traffic on ten fine fescue cultivars. The trial was seeded in September 2012 on a loam in North, Brunswick, NJ. Abrasive wear was applied with Rutgers Wear Simulator and cleated traffic was applied with Cady Traffic Simulator. Traffic tolerance was evaluated in 12 assessment periods (8 passes per assessment period) from autumn 2014 to summer 2017. Traffic tolerance of fine fescues was visually assessed by fullness of turfgrass canopy (FTC), leaf bruising (loss of green color), and green cover determined by digital image analysis. Soil bulk density, verdure and thatch biomass were measured after the twelfth assessment period. Turf cover of fine fescues was affected by traffic forms. Cleated traffic initially reduced FTC but did not affect FTC compared to the non-trafficked control as fine fescues became more mature during the last four assessment periods. Cleated traffic compacted soil and produced greater biomass in the thatch-layer compared to the non-trafficked control. Abrasives wear, on the other hand, caused more thinning of the turf, which greatly reduced biomass in the verdure and thatch layers compared to cleated traffic and non-trafficked control. Generally, cultivars were less tolerant to abrasive wear than cleated traffic; however, cultivars with improved traffic tolerance (Blueray and Beacon hard fescue, and Quatro sheep fescue) maintained a relatively high and similar FTC across both forms of traffic. Results also suggested that

the selection efficiency for traffic tolerance in fine fescues would be better using abrasive wear compared to cleated traffic.

INTRODUCTION

Fine fescues (*Festuca* spp.) are a group of cool-season turfgrass species that have a very fine leaf texture and are often used in mixtures with other cool-season grasses for the home lawn, golf course rough and areas receiving minimal maintenance. Species of fine fescues are tolerant to drought and shade stresses and require less water and fertilizer compared to other commonly used cool-season grasses (Bonos and Huff, 2013).

There are two main categories or complexes of fine fescues, the *Festuca rubra* L. (red fescue) and *F. ovina* L. (sheep fescue) complex (Ruemmele et al. 1995). The *F. rubra* complex has fine-textured, medium to dark green leaves, high shoot density, good uniformity and quality (Bonos and Huff, 2013). This complex contains three economically important species: strong creeping red fescue (*F. rubra* ssp. *rubra* Gaudin), slender creeping red fescue [*F. rubra* ssp. *littoralis* (G. Mey.) Auquier], and Chewings fescue [*F. rubra* ssp. *commutata* Gaudin; syn. *F. rubra* ssp. *fallax* (Thuill.) Nyman]. *Festuca rubra* ssp. *commutata*, have a bunch-type, non-rhizomatous growth habit, while *F. rubra* ssp. *littoralis* and *F. rubra* ssp. *rubra* produce rhizomes, with the latter having longer and more robust rhizomes. The *F. ovina* complex has a bunch-type growth habit and contains two economically important species (Bonos and Huff, 2013): sheep fescue [*F. ovina* L.; syn. *F. ovina* ssp. *hirtula* (Hack. ex Travis) M.J. Wilk.] and hard fescue (*F. brevipila* R. Tracey), which requires less frequent mowing and also great heat and drought tolerance low fertility conditions.

Durability and persistence under traffic stress is an important attribute of widely used turfgrasses. Traffic is a general term often used to describe one or more abiotic stresses, including wear, compaction of soil, soil displacement, and divot removal (Carrow et al., 1992). Soil compaction decreases soil porosity and increases soil strength, which inhibits root growth and water infiltration and drainage. Wear injury results from abrasion, tearing, or shredding of the leaf tissue. Wear is expected to be the dominating stress on sandy rootzones or when soil moisture is limited, while soil compaction dominates on fine-textured soils with high moisture content. Carrow (1980) indicated that wear stress might often be the primary factor contributing to differences among turfgrass species than soil compaction.

Numerous studies found fine fescues as a group is less tolerant to wear and traffic compared to other commonly used cool-season turf species (Carrow et al., 2001; Cereti et al., 2010; Shearman and Beard, 1975). However, under reduced maintenance, some fine fescue cultivars exhibited improved traffic tolerance on golf course fairways, tennis court and cricket square (Horgan et al., 2007; Cortese et al. 2011; Cross et al., 2013). Among fine fescue species, Chewings and hard fescue were more wear tolerant than other fine fescue species (Cross et al., 2013; Cortese et al. ,2011; Grimshaw et al., 2018). A survey conducted by Yue et al. (2017) showed that the ability to withstand traffic is one of the most important attributes for consumers in the U.S. and Canada. Thus, improvement in the traffic tolerance of fine fescues would likely enable greater use of these species by the turf industry.

Enhancing traffic tolerance of fine fescues requires the development of germplasm screening methods to assess the response of fine fescues to traffic. The development of traffic- and wear-stress simulators have facilitated the study of wear and soil compaction either separately or combined. Multiple studies indicated wear was more detrimental to creeping (*Agrostis stolonifera*) and velvet (*Agrostis canina*) bentgrass than soil compaction on sand-based rootzone (Cashel et al. 2005; Samaranayake et al., 2008). Dest et al. (2009) reported wear accounted for 90% of the total treatment variation in the injury of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne*) mixture turf. Park et al. (2011) compared the effect of trampling stress applied with Cady Traffic Simulator (CTS; Henderson et al., 2005) versus wear stress applied with Rutgers Wear Simulator (RWS; Bonos et al., 2001) and found that wear stress caused more injury and was more effective at distinguishing Kentucky bluegrass entries.

The performance of fine fescue species and cultivars may differ by the form of traffic stress. Grimshaw et al. (2018) investigated the heritability of fine fescues using RWS and a golf cart traffic simulator. Resulted indicated that wear stress improved the screening efficiency compared to a simulator imparts both wear and soil compaction. Therefore, the objective of this study was to evaluate forms of traffic stress as a potential factor related to identifying traffic tolerance fine fescues.

MATERIALS AND METHODS

Site Description and Maintenance

This trial was conducted on a Nixon loam (fine-loamy, mixed, mesic Typic Hapludults) at Hort Farm 2 in North Brunswick, NJ. Turf plots were grow-in with annual N rates of 70.8, 86.4, 42.0, 51.8, 39.1, and 48.8 kg ha^{-1} from 2102 to 2017. N was applied as ammonium sulfate, and urea and K were applied as sulfate of potash with 16-0-8 granular N-P_2O_5-K_2O fertilizer. Soil testing indicated that soil pH ranged from 6.0 to 6.7, and soil P and K were no less than 134 and 165 mg kg^{-1}, respectively, from 2014 to 2017. The trial was mowed at 6.4 cm once a week from April to November, except during periods of high air temperature and dry soil when mowing was suspended to avoid bruising damage from tires. Irrigation was applied to avoid severe drought stress.

Summer patch (caused by *Magnaporthiopsis poae*) and dollar spot (caused by *Clarireedia jacksonii*) was suppressed by fluoxastrobin applied at 0.55 kg a.i. ha^{-1} on 15 June, 12 July and 2 Aug. 2013, 14 May, 11 June, 8 July and 1 Aug.2014, 19 May and 15 June 2015, 27 July 2017 in rotation with pyraclostrobin applied at 0.56 kg a.i. ha^{-1} on 6 July, 3 and 18 Aug., 17 Nov. 2015, 23 May, 17 June, 14 July, 12 Aug., 2 Sep. and 31 Oct. 2016, 3 and 24 May, 16 Aug., 22 Sep. 2017. Azoxystrobin and difenoconazole were also used to suppress summer patch and dollar spot at 0.32 and 0.20 kg a.i. ha^{-1}, respectively, on 7 and 21 June, 6 July 2017. Iprodione was also used to suppress dollar spot at 2.29 kg a.i. ha^{-1} on 7 Sep. 2017. Pythium was controlled with cyazofamid applied at 2.75 kg a.i. ha^{-1} on 12 and 26 July 2016. Trifloxystrobin combined with triadimefon was applied to control pink snow mold (caused by *Michrodocium nivale*) at 0.61 kg a.i. ha^{-1} on 21 Dec. 2015. Leaf spot (caused by *Drechslera dictyoides*) was suppressed by penthiopyrad applied at 1.53 kg a.i. ha^{-1} on 12 May and 3 June 2016.

Sod webworm, chinch bugs, and white grubs were controlled using chlorantraniliprole applied at 0.06 kg a.i. ha^{-1} and 0.18 kg a.i. ha^{-1} on 29 Aug. 2013 and 26 July 2014, respectively; imidacloprid applied at 0.55 kg a.i. ha^{-1} and 0.61 kg a.i. ha^{-1} on 11 June 2015 and 17 May 2017; and clothianidin applied at 0.88 kg a.i. ha^{-1} on 4 Oct. 2016.

Broadleaf weeds were controlled by dimethylamine salt of dicamba and 2,4-dichlorophenoxyacetic acid applied at 0.28 and 0.54 kg a.i. ha^{-1}, respectively, on 11 April 2013; 2,4-dichlorophenoxyacetic acid and triclopyr acetic acid applied at 0.54 and 1.12 kg a.i. ha^{-1}, respectively, on 19 April 2014; carfentrazone-ethyl applied at 0.03 kg a.i. ha^{-1}, 2,4-dichlorophenoxyacetic acid at 1.05 kg a.i. ha^{-1}, mecoprop applied at 0.33 kg a.i. ha^{-1}, and dicamba applied at 0.10 kg a.i. ha^{-1} on 31 July 2015 and 28 April 2017. Clopyralid was used to control crabgrass at 0.28 kg a.i. ha^{-1} on 15 April 2014 and 17 April 2015 and 13 April 2017.

Experimental Design and Treatments

This trial used a 2 x 10 factorial split-plot design with four replications. The form of traffic factor was arranged as main plots with two levels: abrasive wear and cleated traffic; and a non-trafficked control was also included for comparison. Abrasive wear was applied with Rutgers Wear Simulator (RWS; Figure 2.1), a 0.8-m wide simulator with rubber paddles mounted on a Toro landscape mower designed to impart wear to aboveground plant parts and minimize soil compaction (Bonos et al., 2001). The RWS was operated at 4.0 km h^{-1} with paddles rotating at 250-rpm. Cleated traffic was applied with a modified Cady Traffic Simulator (CTS; Figure 2.2) developed using a Toro Greens Aerifier (The Toro Co., Bloomington, MN, USA). The cleated “feet” were constructed according to specifications authored by Henderson et al. (2005). The CTS was operated in the forward direction at 1.6 km hr-1.

The machines applying the form of traffic to the respective main plot were operated one pass per week during twelve 8-wk assessment periods from September 2013 through August 2017. The twelve assessment periods were: autumn (24 Sep. to 10 Nov.)

2013, spring (24 April to 9 June 2014), summer (7 July to 24 August 2014), autumn (22 September to 10 November 2014), spring (22 April to 10 June 2015), summer (8 July to 26 August 2014), autumn (24 September to 9 November 2015), spring (28 April to 13 June 2015), summer (12 July to 24 August 2016), autumn (23 September to 10 November 2016), spring (29 April to 12 June 2017) and summer (13 July to 29 August 2017). Turf plots were allowed to recovery (no traffic) between November and April and the four weeks between the spring and summer and summer and autumn traffic periods.

The subplot factor consisted of ten fine fescues cultivars: strong creeping red fescue (*F. rubra* ssp. *rubra* 'Marvel' and 'Garnet'); slender creeping red fescue (*F. rubra* ssp. *littoralis* 'Shoreline' and 'Seabreeze GT'); Chewings fescue (*F. rubra* ssp. *commutata* 'Culumbra II' and 'Radar'); hard fescue (*F. brevipila* 'Aurora Gold', 'Beacon', and 'Blueray'); and sheep fescue (*F. ovina* 'Quatro'). Fine fescue cultivars were seeded into 1.2- x 1.8-m plots in September 2012.

Data Collection

At the endo of each assessment period, plots treated with the RWS and CTS as well as the non-trafficked plots were visually assessed for fullness of turf canopy (FTC; 0 to 100% scale, 100% equaled a full canopy; Figures 2.3 and 2.4) and leaf bruising (1 to 9 scale, 9 equaled no bruising; Figure 2.5 and 2.6). Leaf brusing characterized the loss of green cover with no account for the fullness of turf canopy. Plots with full canpy but yellow or brown color were rated as severe leaf bruising. Visual assessment was conducted by the same rater throughout the twelve assessment periods to reduce rater-to-rater variation. A Canon PowerShot G12 (Canon USA, Inc., Lake Success, NY) digital camera was positioned to capture images of plots within an enclosed box equipped with artificial lighting. Individual digital image size was 1600 x 1064 pixels, and camera settings included a shutter speed of 1/40 s, an aperture of F2.8, an ISO of 100, and a focal length of 7 mm. Images were imported into SigmaScan Pro (v. 5.0, SPSS, Inc., Chicago, IL) for digital image analysis (DIA). Percent green cover was determined according to methods described by Richardson et al. (2001) using batch analysis programming developed by Karcher and Richardson (2005). A hue range of 44 to 100 and a saturation range of 0 to 100 was used in the software to determine the percent green cover.

Surface bulk density and volumetric water content were measured using gamma-ray scattering and detection of thermalized neutrons using a portable surface moisture-density gauge (Model 3411, Troxler Electronic Laboratories, Inc., Research Triangle Park, NC). Soil bulk density and volumetric water content (VWC) were measured (two measurements per plot) in backscatter mode after the 3rd, 6th, and 9th assessment period on 22 September 2014, 21 September 2015, and 18 September 2016, respectively.

After the 12th assessment period on 11 September 2017, two verdure samples were collected from each plot to determine leaf moisture, fresh and dry verdure biomass. Soil bulk density and VWC were measured in three different ways using the moisture-density gauge: i) backscatter mode before verdure removal; ii) backscatter mode after verdure removal; and iii) direct transmission mode at 51-mm depth. Two thatch-layer samples were collected from each plot using a 108-mm diameter lever-action hole cutter (Par Aide Product Company, Lino Lakes, MN). The thickness of thatch-layer was measured in the lab using an F2750IQ electronic indicator (Starrett Co., Athol, MA, USA). Organic matter concentration of the t hatch-layer samples was determined using loss on ignition at 360°C for 12 hours.

Data Analysis

The Dunnett's test was first performed to compare abrasive wear and cleated traffic to the non-trafficked control. The Dunnett's test compares means from each experimental treatment (abrasive wear and cleated traffic) against a control group to see is there is a difference. The procedures for performing Dunnett's test in SAS was described by Holzer and Precht (1992). Data excluded non-trafficked control were then analyzed using a 2 x 10 factorial arranged in a split-plot design with four replications. All analyses were carried out using the Statistical Analysis System (SAS) software package (v. 9.4; SAS Institute) and data were subjected to analysis of variance (ANOVA) using the GLM procedure. Statistically significant main effects and interaction means were separated using Fisher's protected least significant difference test at the 0.05 probability level.

RESULTS AND DISCUSSION

Fullness of Turfgrass Cover

The Dunnett's test indicated that the fullness of turfgrass canopy (FTC) of plots under abrasive wear was always lower than the non-trafficked control (Table 2.1). Cleated traffic initially caused more damage and resulted in a lower FTC compared to non-trafficked control. However, the detrimental effect of cleated traffic on FTC decreased as fine fescue became more mature; the difference between cleated traffic and non-trafficked control become insignificant in the last four assessment periods (Table 2.1). The effect of abrasive wear was more detrimental on FTC than cleated traffic in eight out of twelve assessment periods (Table 2.1). Park et al. (2017) compared the effect of cleated traffic (CTS; Henderson et al., 2005) versus abrasive (RWS; Bonos et al.,

2001) and reported that greater injury and slower recovery on Kentucky bluegrass (*Poa pratensis*), perennial ryegrass (*Lolium perenne*) and tall fescue (*Festuca arundinacea*) under abrasive wear.

The ANOVA indicated that FTC was strongly influenced by cultivar throughout the 12 assessment traffic periods, and the cultivar response depended on the traffic form during spring and summer of 2015 (Table 1). Greater differences in FTC among fine fescues occurred under abrasive wear than cleated traffic (Table 2.2). Generally, when the interactions between cultivar and traffic form were significant, worn plots had lower FTC compared to plots subjected to cleated traffic when differences between the traffic forms were evident (Table 2.2). However, Blueray and Beacon hard fescue, and Quatro sheep had the greatest FTC among all the cultivars and the FTC response did not differ across the traffic forms. Radar and Culumbra II Chewings fescue, Marvel and Garnet strong creeping red fescue, and Shoreline slender creeping red fescue were more vulnerable under abrasive wear compared to cleated traffic (Table 2.2). Seabreeze GT slender creeping exhibited the poorest FTC under both forms of traffic (Table 2.2). When the FTC response of fine fescues was independent of traffic form in ten out of twelve assessment periods (Table 2.1). Blueray and Beacon hard fescue, Quatro sheep fescue and Radar Chewings fescue were among the group of cultivars with the greatest FTC from autumn 2013 to spring 2017 while Seabreeze GT slender creeping red fescue and Aurora Gold hard fescue had the poorest FTC for these assessment periods. (Table 2.3).

Bonos et al. (2001) noted the importance of identifying the environmental stress that causes different traffic responses to improve selection efficiency. In this study, the FTC response of fine fescues to traffic was significantly influenced by summer patch disease (caused by *Magnaporthe poae*) during summer 2017. Blueray, Beacon and Aurora Gold hard fescue and Quatro sheep fescue had the most severe summer patch infection among ten fine fescue cultivars (Table 2.4). The performance of these cultivars under wear stress was compromised by greater susceptibility to disease. Park et al. (2010) also observed more severe damage, and greater difference among Kentucky bluegrass cultivars under wear stress applied during summer and autumn than spring.

Leaf Bruising

Leaf bruising response was reported on Kentucky bluegrass, perennial ryegrass, and tall fescue by Park et al. (2017) using the Rutgers Wear Simulator (RWS). In this study, the Dunnett's test indicated that abrasive wear resulted in more severe leaf bruising than untreated control throughout the study, while leaf bruising was only evident in the first half of the study under cleated traffic (Table 2.5).

Leaf bruising response of fine fescue cultivars depended on traffic forms during six out of twelve assessment periods (Table 2.5). Greater differences in leaf bruising among fine fescue cultivars occurred under abrasive wear than cleated traffic, and season appeared to influence the leaf bruising response of fine fescue cultivars (Table 2.6). Quatro sheep fescue was the least bruised cultivar during autumn but was more prone to leaf bruising during summer. In contrast, leaf bruising of Radar Chewings fescue was more severe during autumn than spring and summer (Table 2.6). When the leaf bruising of cultivars was independent of the traffic form, Quatro sheep fescue was always within the group of cultivars with most severe leaf bruising while Beacon hard fescue and Garnet strong creeping red fescue exhibited least leaf bruising among all cultivars (Table 2.7).

Green Cover

The Dunnett's test indicated that the green cover of plots treated with abrasive wear was always lower than the non-trafficked control (Table 2.8). Cleated traffic also reduced the green cover of fine fescue turf and was different from the green cover of non-trafficked turf in seven out of twelve assessment period (Table 2.9).

Cultivar responses in green cover were always independent of the form of traffic, and there were significant differences among fine fescue cultivars in eleven out of twelve assessment periods (Table 2.8). Blueray and Beacon hard fescue, and Radar Chewings fescue were most frequently ranked among cultivars with the greatest green cover (Table 2.9). While having poor FTC, Shoreline and Seabreeze GT slender creeping red fescue was the next most frequent rankings among cultivars with the greatest green cover (Table 2.9).

The difference between green cover and FTC was partially due to the fact that digital images only quantify green cover of plots from a two-dimensional vertical view while FTC was visually assessed from a three-dimensional view. The damage on the turf canopy was covered by overlaying leaf blades of fine fescue due to the cutting height (6.4-cm), which resulted in an overestimation of green cover since digital images assessment was only based on a two-dimensional view. It appears that leaf bruising also influenced the green cover response of fine fescues. The contradiction between visual assessment and green cover responses was observed on Quatro sheep fescue, which exhibited great FTC while had the poorest green cover due to severe leaf bruising.

Soil Volumetric Water Content and Bulk Density

Soil volumetric water content (VWC) and bulk density were measured after the third, sixth and ninth assessment periods using the Troxler moisture-density gauge set in backscatter mode. Greater VWC and bulk density were detected with cleated traffic treatment compared to non-traffic control (Table 2.10). Abrasive wear also increased soil bulk density compared to non-trafficked control but to a less extent than cleated traffic (Table 2.10). The results are consistent with Park et al. (2017), who reported a compacting effect of abrasive wear and cleated traffic on tall fescue (*Festuca arundinacea*), perennial ryegrass (*Lolium perenne*), and Kentucky bluegrass (*Poa pratensis*).

Cultivar main effect had a significant impact on surface VWC and bulk density (Table 2.10). Quatro had the greatest VWC among all fine fescue cultivars in autumn 2014 and autumn 2015 (Table 2.11). Aurora Gold hard fescue plots had the greatest bulk density while Radar Chewings fescue and Beacon hard fescue plots had the lowest bulk density among all fine fescue cultivars in all three measurement dates (Table 2.11). It is important to note that surface VWC and bulk density were measured on plots with verdure and thatch layers present. Thus, the great FTC of Beacon hard fescue and Radar Chewings fescue contributed to a lower bulk density.

After the twelfth assessment period in autumn 2017, soil VWC and bulk density were measured in three modes: backscatter mode with verdure, backscatter mode without verdure, and direct transmission mode at 58-mm depth. Cleated traffic compacted soil and resulted in greater bulk density and VWC than the non-trafficked control and abrasive wear in all three measuring modes (Table 2.12). Abrasive wear also increased soil bulk density but did not change soil VWC compared to the non-trafficked control (Table 2.12).

Quatro sheep fescue plots had the greatest VWC among all fine fescue cultivars while Seabreeze GT slender creeping red fescue plots and Garnet strong creeping red fescue plots had the lowest VWC in all three measuring modes (Table 2.13). Aurora Gold plots had the most compacted soil followed by and Seabreeze GT slender crepping red fescue plots while Radar Chewings fescue plots produced the least compacted soil among all fine fescue cultivars (Table 2.13).

Biomass of Verdure and Thatch

The thinning effect of abrasives greatly reduced biomass in verdure- and thatch-layer compared to the non-trafficked control and cleated traffic (Table 2.14). Verdure biomass in plots received cleated traffic was not different from the non-trafficked control. Surprisingly, the trampling action of cleated traffic condensed the thatch and produced greater biomass in the thatch-layer (Table 2.14). Samaranayake et al. (2008) suggested that the accumulation of organic matter (verdure, thatch, and mat) in turfgrass limited the effect trampling effect (soil compaction). Thus, in this study, the detrimental effect of cleated traffic on FTC decreased as fine fescue became more mature.

Cultivar main effects on biomass of verdure and thatch were significant and independent of the form of main traffic effect (Table 2.14). Quatro sheep fescue, Beacon and Blueray hard fescue, and Radar and Culumbra II Chewings fescue were among the cultivars with the greatest verdure biomass (Table 2.15). Radar Chewings had the greatest thatch biomass followed by Marvel and Garnet strong creeping red fescue and Beacon hard fescue,

CONCLUSION

The ability of fine fescue turf to maintain a dense cover was affected by traffic forms. Cleated traffic resulted in more compacted soil than abrasive wear. However, the detrimental effect of cleated traffic on FTC decreased due to the maturation of grass and the accumulation of organic matter. Abrasive wear applied with RWS caused greater damage to the fullness of turf cover (FTC) than cleated traffic. Generally, cultivars were less tolerant to abrasive wear than cleated traffic. However, cultivars maintained high FTC under abrasive wear also demonstrated an improved ability to tolerate cleated traffic. Abrasive wear also resulted in a greater separation in FTC among fine fescue cultivars, which improved the selection efficiency in evaluating traffic tolerance. In addition, abrasive wear was also effective in selecting cultivars that are resistant to leaf bruising. Green cover determined by digital image analysis was a good supplement to visual assessments when evaluating wear or traffic tolerance; however, caution is needed in interpreting the results as the green cover response was overestimated due to the overlaying of fine fescue leaf blades. It is important to identify the confounding environmental factors that might change traffic responses of fine fescues. In this study, the response of fine fescues to abrasive wear and cleated traffic were significantly influenced by summer patch disease, the ability of disease sensitive cultivars to tolerate traffic was compromised under high disease pressure.

These results advanced our understanding of the effect of traffic forms on fine fescue. The thinning and bruising effects of the abrasive and compacting effect of the cleated traffic can be used by turf breeders to improve screening efficacy in selecting traffic tolerant fine fescue cultivars.

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Table 2.1 Fullness of turfgrass cover as affected by form of traffic and cultivar during a 12 assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

	2013	2014	2014	2014	2015	2015	2015	2016	2016	2016	2017	2017
	Aut.	Spr.	Sum.	Aut.	Spr.	Sum.	Aut.	Spr.	Sum.	Aut.	Spr.	Sum.
						Dunnett's Test						
	----- mean difference compare to control -----											
Cleated - Control	-26***	-28***	-25***	-28***	-23***	-19***	-12***	-6***	-1 [ns]	-1 [ns]	4 [ns]	-2 [ns]
Worn - Control	-13***	-30***	-31***	-27***	-33***	-27***	-24***	-21***	-22***	-25***	-23***	-29***
						ANOVA						
Source of variation												
Traffic Form (TF)[†]	*	ns[§]	ns	ns	*	*	*	*	**	***	**	***
Cultivar	***	***	***	***	***	***	***	***	*	***	***	*
TF x Cultivar	ns	ns	ns	ns	***	**	ns	ns	ns	ns	ns	ns

[†] Cleated and Worn trafficked with the Cady Traffic Simulator and Rutgers Wear Simulator, respectively for 8 weeks during the assessment period

* Significant at $p \leq 0.05$.

** Significant at $p \leq 0.01$.

*** Significant at $p \leq 0.0001$.

[§] ns, non-significant

Table 2.2 Fullness of turfgrass cover as affected by the interaction of traffic form and cultivar during six assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

	2015 Spring		2015 Summer	
	Cleated	Worn	Cleated	Worn
	-- 0 to 100%; 100% = full cover --			
Cultivar				
Beacon [HD¶]	81	84	78	81
Blueray [HD]	77	83	73	69
Quatro [SH]	76	79	76	71
Radar [CH]	75	64	74	74
Culumbra II [CH]	76	63	70	58
Marvel [ST]	73	46	74	58
Garnet [ST]	73	50	74	53
Shoreline [SL]	73	55	65	53
Aurora Gold [HD]	65	61	60	59
Seabreeze GT [SL]	59	45	51	45
LSD (0.05) Row	9		11	
LSD (0.05) Column	8		10	

† Cleated and Worn trafficked with the Cady Traffic Simulator and Rutgers Wear Simulator, respectively for 8 weeks during the assessment period

¶ Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 2.3 Cultivar main effect on fullness of turfgrass cover during the initial four and final two assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

Main effect	2013 Autumn	2014 Spring	2014 Summer	2014 Autumn	2015 Autumn	2016 Spring	2016 Summer	2016 Autumn	2017 Spring	2017 Summer
	---------------------------------- 0 to 100%; 100% = full cover ----------------------------------									
Radar [CH¶]	82	64	70	69	79	85	85	81	66	74
Beacon [HD]	79	69	71	75	82	85	88	87	61	49
Quatro [SH]	67	75	73	74	76	83	83	83	66	53
Blueray [HD]	74	66	66	68	79	83	83	86	64	35
Marvel [ST]	68	68	69	68	73	66	73	67	72	78
Garnet [ST]	61	66	64	66	73	74	75	62	68	78
Culumbra II [CH]	60	64	63	63	71	81	78	69	69	66
Shoreline [SL]	66	66	62	62	66	76	69	53	59	66
Aurora Gold [HD]	45	43	51	60	70	74	76	71	64	46
Seabreeze GT [SL]	42	44	47	53	51	68	52	36	46	56
LSD (0.05)	7	8	9	7	10	8	8	9	9	19

[¶] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 2.4 Cultivar main effect on summer patch disease damage during the initial four and final two assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

Main effect	2017 June	2017 July
	----------------- 1 to 9; 9 = no disease -----------------	
Marvel [ST¶]	9.0	9.0
Garnet [ST]	9.0	9.0
Shoreline [SL]	9.0	9.0
Seabreeze GT [SL]	9.0	9.0
Culumbra II [CH]	9.0	8.8
Radar [CH]	8.8	8.5
Aurora Gold [HD]	4.8	3.7
Quatro [SH]	4.9	2.8
Beacon [HD]	4.0	2.8
Blueray [HD]	2.6	1.8
LSD (0.05)	1.5	1.3

[¶] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 2.5 Leaf bruising as affected by form of traffic and cultivar during a 12 assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

	2013 Aut.	2014 Spr.	2014 Sum.	2014 Aut.	2015 Spr.	2015 Sum.	2015 Aut.	2016 Spr.	2016 Sum.	2016 Aut.	2017 Spr.	2017 Sum.
							Dunnett's Test					
	-- mean difference compare to control --											
Cleated - Control	-2.8***	-3.0***	-2.3***	-0.8***	-1.0***	-1.0***	-0.1^{ns}	0^{ns}	-0.2^{ns}	0^{ns}	0^{ns}	-0.4^{ns}
Worn - Control	-5.0***	-3.8***	-2.5***	-3.3***	-1.8***	-2.9***	-3.2***	-0.2***	-3.1***	-3.4***	-0.4***	-1.4***
							ANOVA					
Source of variation												
Traffic Form (TF)[†]	**	ns[§]	ns	*	*	***	***	ns	**	**	*	**
Cultivar	***	**	***	***	***	***	***	***	***	**	***	***
TF x Cultivar	***	ns	*	ns	ns	ns	*	ns	***	**	ns	**

[†] Cleated and Worn trafficked with the Cady Traffic Simulator and Rutgers Wear Simulator, respectively for 8 weeks during the assessment period

* Significant at p≤0.05.

** Significant at p≤0.01.

*** Significant at p≤0.0001.

[§] ns, non-significant

Table 2.6 Leaf bruising as affected by the interaction of traffic form and cultivar during six assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

	2013 Autumn		2014 Summer		2015 Autumn		2016 Summer		2016 Autumn		2017 Summer	
	-- 1 to 9; 9 = green --											
Cultivar	Cleated	Worn [†]	Cleated	Worn	Cleated	Worn	Cleated	Worn	Cleated	Worn	Cleated	Worn
Marvel [ST¶]	6.8	4.0	8.0	7.0	9.0	5.3	9.0	8	9.0	5.8	9.0	9.0
Garnet [ST]	6.0	3.3	7.3	7.3	8.8	5.0	9.0	5.8	8.8	5.5	9.0	8.8
Aurora Gold [HD]	5.3	5.3	6.7	7.3	9.0	6.5	8.7	6.3	9.0	5.8	8.3	5.0
Seabreeze GT [SL]	6.5	4.3	6.0	6.5	9.0	7.0	7.5	4.0	9.0	5.8	9.0	8.3
Beacon [HD]	6.0	3.8	7.0	7.3	9.0	5.5	8.3	6.8	9.0	4.0	8.0	8.0
Culumbra II [CH]	5.8	3.5	6.3	5.8	8.3	5.0	8.8	3.8	9.0	6.5	8.8	8.0
Blueray [HD]	5.3	3.0	6.3	6.8	9.0	6.5	8.7	7.3	9.0	5.8	6.7	4.8
Radar [CH]	7.0	2.5	7.3	7.5	7.3	2.8	8.8	5.0	9.0	4.5	8.8	8.3
Shoreline [SL]	6.5	3.0	5.5	4.8	9.0	7.0	7.5	4.0	9.0	5.0	8.8	8.3
Quatro [SH]	7.0	7.3	6.5	5.0	8.8	5.8	8.5	5.3	9.0	6.5	6.0	2.8
LSD (0.05) Row	1.2		0.7		0.9		1.0		0.9		1.3	
LSD (0.05) Column	0.9		0.7		0.9		0.9		0.7		1.1	

[†] Cleated and Worn trafficked with the Cady Traffic Simulator and Rutgers Wear Simulator, respectively for 8 weeks during the assessment period

[¶] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 2.7 Cultivar main effect on leaf bruising during the initial four and final two assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

Main effect	2014 Spring	2014 Autumn	2015 Spring	2015 Summer	2016 Spring	2017 Spring
	---------------- 1 to 9; 9 = completely green ----------------					
Marvel [ST¶]	9.0	6.8	7.8	8.0	9.0	8.9
Seabreeze GT [SL]	8.9	7.8	7.5	7.0	9.0	8.9
Beacon [HD]	8.6	7.5	7.4	8.3	8.6	8.7
Shoreline [SL]	8.8	7.8	7.4	6.5	9.0	9.0
Garnet [ST]	9.0	5.9	7.5	7.6	9.0	9.0
Aurora Gold [HD]	8.1	7.3	7.0	7.9	8.4	8.9
Blueray [HD]	8.3	7.7	6.9	6.9	9.0	8.7
Radar [CH]	8.4	4.3	8.0	6.6	8.9	8.7
Culumbra II [CH]	8.1	5.0	7.5	5.9	9.0	9.0
Quatro [SH]	8.0	6.3	6.6	5.9	7.0	8.0
LSD (0.05) Column	0.5	2.0	0.5	0.5	0.4	0.4

[¶] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 2.8 Green cover as affected by form of traffic and cultivar during a 12 assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

	2013 Aut.	2014 Spr.	2014 Sum.	2014 Aut.	2015 Spr.	2015 Sum.	2015 Aut.	2016 Spr.	2016 Sum.	2016 Aut.	2017 Spr.	2017 Sum.
						<u>Dunnett's Test</u>						
						---------- mean difference compare to control ----------						
Cleated - Control	-19***	-4***	-4***	-5***	-3***	-21***	-5***	-6***	-5***	-11***	-3^{ns}	-4 ^{ns}
Worn - Control	-34***	-13***	-7***	-12***	-18***	-34***	-17***	-12***	-24***	-27***	-13***	-7***
						<u>ANOVA</u>						
Source of variation												
Traffic Form (TF) [†]	*	*	**	**	**	**	***	**	**	**	*	*
Cultivar	ns[§]	***	***	***	***	***	***	***	***	***	***	***
TF x Cultivar	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[†] Cleated and Worn trafficked with the Cady Traffic Simulator and Rutgers Wear Simulator, respectively for 8 weeks during the assessment period

* Significant at p≤0.05.

** Significant at p≤0.01.

*** Significant at p≤0.0001.

[§] ns, non-significant

Table 2.9 Cultivar main effect on green cover during the initial four and final two assessment periods of traffic on fine fescues seeded in September 2012 on a loam in North Brunswick, NJ.

	2013 Autumn	2014 Spring	2014 Summer	2014 Autumn	2015 Spring	2015 Summer	2015 Autumn	2016 Spring	2016 Summer	2016 Autumn	2017 Spring	2017 Summer
Cultivar	-- 0 to 100%; 100% = full green cover --											
Marvel [ST¶]	52	58	57	78	59	45	77	77	65	60	95	96
Radar [CH]	47	65	60	70	72	38	72	81	54	59	85	92
Garnet [ST]	48	57	50	76	60	42	74	79	54	54	92	94
Beacon [HD]	45	59	58	83	71	50	79	77	56	52	64	77
Shoreline [SL]	47	66	44	85	69	35	82	83	43	47	82	84
Culumbra II [CH]	41	62	47	70	68	33	74	77	44	62	92	90
Seabreeze GT [SL]	47	61	52	83	64	38	81	85	32	44	84	89
Blueray [HD]	46	61	58	84	70	39	82	80	52	61	37	57
Quatro [SH]	49	58	48	84	67	29	75	67	48	59	74	59
Aurora Gold [HD]	41	46	54	80	63	38	80	70	43	57	83	57
LSD (0.05) Column	ns	7	2	4	4	4	4	6	13	9	8	7

[¶] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 2.10 Surface volumetric water content and bulk density as measured by a Troxler moisture-density gauge set in backscatter mode at the end of autumn traffic periods in 2014, 2015 and 2016.

	2014		2015		2016	
	VWC[f]	Bulk density	VWC	Bulk density	VWC	Bulk density
			Dunnett's Test			
	---------- mean difference compare to control ----------					
	$m^3\ m^{-3}$	$g\ cm^{-3}$	$m^3\ m^{-3}$	$g\ cm^{-3}$	$m^3\ m^{-3}$	$g\ cm^{-3}$
Cleated - Control[†]	1.5***	0.13***	1.1***	0.10***	1.4***	0.11***
Worn - Control	0 [ns]	0.06***	-0.1[ns]	0.04***	-0.3[ns]	0.07***
			ANOVA			
Source of variation						
Traffic Form (TF)	**	***	***	**	***	***
Cultivar	***	***	***	***	ns	***
TF x Cultivar	ns[§]	ns	ns	ns	ns	ns

[†] Cleated and Worn trafficked with the Cady Traffic Simulator and Rutgers Wear Simulator, respectively for 8 weeks during the assessment period

* Significant at p≤0.05.

** Significant at p≤0.01.

*** Significant at p≤0.0001.

[§] ns, non-significant

[f] Surface bulk density and volumetric water content were measured by Troxler, Model 3440

Table 2.11 Cultivar main effect on soil volumetric water content and bulk density as measured by a Troxler moisture-density gauge set in backscatter mode at the end of autumn traffic periods in 2014, 2015 and 2016.

	2014		2015		2016	
	Autumn	Autumn	Autumn	Autumn	Autumn	Autumn
	VWC	Bulk Density	VWC	Bulk Density	VWC	Bulk Density
Cultivar	$m^3 m^{-3}$	$g cm^{-3}$	$m^3 m^{-3}$	$g cm^{-3}$	$m^3 m^{-3}$	$g cm^{-3}$
Aurora Gold [HD¶]	17.2	1.15	12.1	1.11	11.4	0.98
Seabreeze GT [SL]	17.1	1.13	11.9	1.02	12.0	0.94
Quatro [SH]	18.1	1.07	13.1	1.02	12.7	0.96
Garnet [ST]	17.1	1.05	11.4	1.00	12.0	0.93
Culumbra II [CH]	17.2	1.07	11.6	0.95	12.3	0.92
Shoreline [SL]	16.6	1.05	11.9	0.97	11.7	0.88
Blueray [BL x HD¶]	16.3	1.01	11.8	0.98	11.0	0.88
Marvel [ST]	17.2	1.01	11.2	0.95	11.5	0.88
Beacon [HD]	16.1	0.98	11.3	0.94	11.4	0.83
Radar [CH]	16.1	0.94	11.2	0.88	11.4	0.81
LSD (0.05)	0.8	0.03	0.7	0.06	ns	0.04

[§] Surface bulk density and volumetric water content were measured by Troxler, Model 3440

[¶] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 2.12 Soil volumetric water content and bulk density as measured at different depth by a Troxler moisture-density gauge after twelve assessment periods in September 2017

	Surface with verdure (backscatter)		Surface without verdure (backscatter)		58-mm depth (direct transmission)	
	VWC[f]	Bulk density	VWC	Bulk density	VWC	Bulk density
	Dunnett's Test					
	---------- mean difference compare to control ----------					
	$m^3\ m^{-3}$	$g\ cm^{-3}$	$m^3\ m^{-3}$	$g\ cm^{-3}$	$m^3\ m^{-3}$	$g\ cm^{-3}$
Cleated - Control[†]	2.1***	0.10***	2.3***	0.09***	2.1***	0.10***
Worn - Control	0.3[ns]	0.06***	0.2 [ns]	0.06***	0.1 [ns]	0.05***
	ANOVA					
Source of variation						
Traffic Form (TF)	**	***	**	***	***	***
Cultivar	***	***	***	***	***	***
TF x Cultivar	ns	ns	ns	ns	ns	ns

[†] Cleated and Worn trafficked with the Cady Traffic Simulator and Rutgers Wear Simulator, respectively for 8 weeks during the assessment period

* Significant at $p \leq 0.05$.

** Significant at $p \leq 0.01$.

*** Significant at $p \leq 0.0001$.

[§] ns, non-significant

[f] Surface bulk density and volumetric water content were measured by Troxler, Model 3440

Table 2.13 Cultivar main effect on soil volumetric water content and bulk density as measured at different depth by a Troxler moisture-density gauge after twelve assessment periods in September 2017

	Surface with verdure (backscatter)		Surface without verdure (backscatter)		58-mm depth (direct transmission)	
	VWC	Bulk Density	VWC	Bulk Density	VWC	Bulk Density
Cultivar	$m^3\ m^{-3}$	$g\ cm^{-3}$	$m^3\ m^{-3}$	$g\ cm^{-3}$	$m^3\ m^{-3}$	$g\ cm^{-3}$
Aurora Gold [HD¶]	15.6	1.08	16.4	1.21	16.2	1.43
Seabreeze GT [SL]	14.8	1.01	16.1	1.14	15.8	1.39
Quatro [SH]	17.6	1.00	18.1	1.13	18.0	1.37
Blueray [HD]	16.6	0.97	17.5	1.09	17.1	1.33
Culumbra II [CH]	16.2	0.95	16.9	1.08	16.8	1.32
Garnet [ST]	15.4	0.95	15.7	1.08	16.2	1.30
Beacon [HD]	15.6	0.93	16.4	1.06	16.6	1.30
Shoreline [SL]	15.9	0.94	17.3	1.06	17.1	1.29
Marvel [ST]	15.6	0.92	16.7	1.03	16.3	1.27
Radar [CH]	16.5	0.81	17.4	0.91	17.3	1.12
LSD (0.05)	0.7	0.05	0.7	0.05	0.7	0.05

[§] Surface bulk density and volumetric water content were measured by Troxler, Model 3440

[¶] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 2.14 Biomass of verdure and thatch-layer as affected by form of traffic after twelve assessment periods in September 2017

	Verdure	Thatch
	Dunnett's Test	
	---------------------- mean difference compares to control (kg m^{-2}) ----------------------	
Cleated - Control[†]	-0.04^{ns}	0.19***
Worn - Control	-0.10***	-0.03^{ns}
	ANOVA	
Source of variation		
Traffic Form (TF)	*	*
Cultivar	*	***
TF x Cultivar	ns	ns

[†] Cleated and Worn trafficked with the Cady Traffic Simulator and Rutgers Wear Simulator, respectively for 8 weeks during the assessment period

* Significant at $p \leq 0.05$.

** Significant at $p \leq 0.01$.

*** Significant at $p \leq 0.0001$.

[§] ns, non-significant

[ǂ] Biomass = dry weight ÷ sampling area

Table 2.15 Cultivar main effect on biomass of verdure and thatch-layer after twelve assessment periods in September 2017

	Verdure	Thatch
Cultivar	---------------------------------- $kg\ m^{-2}$	----------------------------------
Quatro [SH¶]	0.29	2.09
Beacon [HD]	0.28	2.29
Radar [CH]	0.27	2.58
Aurora Gold [HD]	0.21	2.16
Culumbra II [CH]	0.25	2.25
Shoreline [SL]	0.25	2.15
Marvel [ST]	0.24	2.38
Garnet [ST]	0.22	2.31
Blueray [HD]	0.25	2.16
Seabreeze GT [SL]	0.20	2.35
LSD (0.05)	0.06	0.19

[†] Leaf moisture = (fresh weight -dry weight) ÷ fresh weight

[‡] Biomass = dry weight ÷ sampling area

[¶] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Figure 2.1 Abrasive wear applied with Rutgers Wear Simulator (RWS) developed by Bonos et al. (2012)

Figure 2.2 Cleated traffic applied with Cady Traffic Simulator (CTS) develop by Henderson et al. (2005)

Figure 2.3 Fullness of turf cover rated at 100% by a trained evaluator

Figure 2.4 Fullness of turf cover rated at 15% by a trained evaluator

Figure 2.5 Leaf bruising rated at 9 (no bruising) by a trained evaluator

Figure 2.6 Leaf bruising rated at 1 (severe leaf bruising) by a trained evaluator

CHAPTER 3 Performance of Ten Fine Fescues Cultivars under Abrasive Wear during Three Seasons

ABSTRACT

The response of turfgrass to wear can vary based on the season during which wear stress occurs. The objective of this study was to assess the relative tolerance of ten fine fescue cultivars to abrasive wear during the seasons of spring, summer, and autumn. The trial was seeded in September 2012 on a loam in North Brunswick, NJ. Abrasive wear was applied in spring (April-May), summer (July- August), autumn (October-November) from autumn 2013 to summer 2017. Wear tolerance of fine fescues was visually assessed by fullness of turfgrass canopy (FTC; 0 to 100%; 100% = full cover) and leaf bruising (1 to 9; 9= dark green, no bruising). Green cover was determined by digital image analysis was included to supplement visual assessment. The ability of fine fescues to maintain a uniform and full canopy in different seasons was positively associated with the FTC observed in non-worn plots. Summer wear resulted in greater damage among fine fescues than spring and autumn in the second and third year of assessment. However, the damage during summer was confounded by high disease pressure and heat stress which made the evaluation of traffic tolerance more difficult and less accurate. Cultivar differences during spring were less evident than summer but greater than autumn. Screening for fine fescues with improved ability to withstand abrasive wear can be more effective during spring to avoid confounding factors during summer. Leaf bruising response of fine fescue to abrasive wear is complicated by the fact that responses varied with the season. Evaluation of this characteristic needs to be conducted in both the summer and autumn.

INTRODUCTION

Season has a great impact on the biological and physiological characteristics of turfgrass. As a result, the response of turfgrass to wear can vary based on the season during which wear stress occurs.

Cool-season (C3) species, due to their less efficient photosynthetic pathway, are more vulnerable to heat and drought stress than warm-season (C4) turfgrass species. During drought stress, the deterioration of cool-season grasses can be accelerated, and the detrimental effects of traffic can be more noticeable compared to warm-season grasses (Braun, 2017). Park et al. (2010) observed more severe damage and greater difference among Kentucky bluegrass (*Poa pratensis*) cultivars under wear stress applied during summer and autumn than spring. A three-year experiment conducted in Finland also found wear tolerance of cool-season turfgrass species was significantly affected by season (Taivalmaa et al., 1998).

Bonos et al. (2001) noted the importance of identifying the environmental factors that cause different traffic responses to improve selection efficiency. It is important to investigate wear tolerance of fine fescues in different seasons to identify broadly adapted cultivars with improved wear tolerance. The objective of this study was to assess the relative tolerance of ten fine fescue cultivars to abrasive wear during the seasons of spring, summer, and autumn.

MATERIALS AND METHODS

Site Description and Maintenance

Ten fine fescue cultivars were seeded into 1.2 x 1.8 m plots in September 2012 on a Nixon loam (fine-loamy, mixed, mesic Typic Hapludults) at Hort Farm 2 in North Brunswick, NJ. Site maintenance was described in Chapter one.

Experimental Design and Treatments

This trial used a 3 x 10 factorial arranged in a split-plot design with four replications. The main plot factor had three seasons of wear stress applied in spring (April-May), summer (July- August), autumn (October-November); a non-worn control was included. The subplot factor consisted of ten fine fescues cultivars described in Chapter one.

Abrasive was applied with Rutgers Wear Simulator (RWS), a 0.8-m wide simulator designed to paddle and abrade aboveground plant parts while minimizing compaction of the soil (Bonos et al., 2001). The RWS was operated at 4.0 km h^{-1} with paddles rotating at 250 rpm across main plots. Wear treatment was initiated on 1-year old fine fescues in September 2013. Autumn wear plots received eight passes of RWS (one pass per week) from September to November in 2013, 2014, and 2015, respectively. Spring wear received eight passes of RWS (one pass per week) from April to June in 2014, 2015, and 2016, respectively. Summer wear received eight passes of RWS (one pass per week) from July to August in 2014, 2015, and 2016, respectively.

Data Collection and Analysis

Fullness of turf cover (FTC; 0-100% scale, 100%=full canopy) were visually assessed on both non-worn and worn plots after wear in each season. Leaf bruising (1 to 9 scale, 9=no bruising) was visually assessed on worn plots after each wear season. Visual assessment was conducted by a trained rater throughout the experiment. A Canon PowerShot G12 (Canon USA, Inc., Lake Success, NY) digital camera was positioned to capture images of plots within an enclosed box equipped with artificial lighting. The individual digital image size was 1600 x 1064 pixels and camera settings included a shutter speed of 1/40 s, an aperture of F2.8, ISO of 100, and a focal length of 7 mm. Images were imported into SigmaScan Pro (v. 5.0, SPSS, Inc., Chicago, IL) for digital image analysis (DIA). Green cover was determined using batch analysis programming developed by Karcher and Richardson (2005). A hue range of 44 to 100 and a saturation range of 0 to 100 was used in the software to determine the percent green cover.

The analyses were performed on worn and non-won turf for FTC, leaf bruising, and green cover. Statistical analyses were carried out using the Statistical Analysis System (SAS) software package (v. 9.4; SAS Institute). Data were subjected to analysis of variance (ANOVA) using the GLM procedure for a split-plot design. Statistically significant main effects and interaction means were separated using Fisher's protected least significant difference test at the 0.05 probability level.

RESULTS AND DISCUSSION

The FTC and green cover of fine fescue under worn condition and under non-worn condition were positively correlated (Table 3.1). Cashel et al. (2005) reported that the ranking of creeping bentgrass (*Agrostis stolonifera*) and velvet (*Agrostis canina*) bentgrass performance under traffic were correlated with turf performance observed in non-trafficked plots. Trenholm et al. (2000) suggested that a greater quantity of tissue allows turf to absorb the impact of injury and leads to a positive correlation between increased shoot density and wear.

Fullness of Turf Canopy (FTC)

Fine fescue cultivar factor interacted with the season of wear in all three years for the FTC (Table 3.2). The FTC initially was lowest during autumn of the first year under worn condition due to the immaturity of the plots during autumn 2013. Lower FTC was observed during summer than spring and autumn in the second and third year of assessment (Table 3.2). The improved hard fescue cultivar Beacon exhibited greater FTC compared to the older cultivars Aurora Gold in all the seasons evaluated (Table 3.3). This confirms the findings of Cortese et al. (2011) and Cross et al. (2013) who also reported enhanced wear tolerance of Beacon hard fescue. Slender creeping red fescue Seabreeze GT was among the cultivars with the lowest FTC throughout the experiment.

It is important to note that wear tolerance of fine fescues during summer was compromised by high disease pressure and heat stress. The confounding factors (disease pressure and heat stress) made the assessment of traffic tolerance of fine fescues more complicated and less accurate during summer. Park et al. (2010) observed a lower FTC after summer wear and a greater canopy loss during autumn on Kentucky bluegrass under abrasive wear applied with RWS (96 passes during a 6-week period). The author also indicated that the performance of disease-susceptible Kentucky bluegrass cultivars under wear stress were compromised during the season when disease pressure was high. In this study, cultivar differences during spring was less evident than summer but still greater than autumn. Thus, screening for fine fescues with improved ability to withstand abrasive wear might be more effective and accurate during spring to avoid high disease pressure and other confounding factors during summer.

Leaf Bruising

Leaf bruising of fine fescue cultivars depended on the season of evaluation (interaction) in all three years (Table 3.4). Leaf bruising of fine fescues was more severe during autumn and summer wear than spring wear in all three years.

Due to the immaturity of the plots, most cultivars had more severe leaf bruising in autumn than summer in the first year (Table 3.5). Leaf bruising response to seasonal wear was more consistent during the second and third year. Quatro sheep fescue, Garnet and Marvel strong creeping red fescue was more susceptible to leaf bruising during summer than autumn while radar Chewings fescue and Shoreline and Seabreeze GT slender creeping red fescue were more bruised during autumn than summer (Table 3.5). Blueray and Aurora Gold hard fescue were the only cultivars that had similar and mild leaf bruising (ratings > 5) in both autumn and summer (Table 3.5). As leaf bruising of fine fescue cultivars depended on the season of wear, it is important to conduct wear in different seasons to better evaluate leaf bruising tolerance of fine fescues.

Leaf bruising was also reported on tall fescue (*Festuca arundinacea*), perennial ryegrass (*Lolium perenne*), and Kentucky bluegrass (*Poa pratensis*) under abrasive wear applied in autumn (Part et al., 2017). The author observed moderate bruising injury after eight passes of RWS, and the injury intensified as the number of passes increased. Leaf bruising tended to be independent of the FTC; cultivars maintained a relatively high FTC can still be vulnerable to leaf bruising, especially during autumn and summer. Dowgiewicz et al. (2011) reported significant losses in color to the upper foliage of creeping and velvet bentgrass under wear; however, wear caused no visual loss in grass cover and shoot density.

Green Cover

Fine fescue cultivar factor interacted with the season of wear in all three years (Table 3.6). Beacon and Blueray hard fescue, Quatro sheep fescue and Radar Chewings fescue occurred in the group of cultivars with the greatest green cover most frequently (Table 3.7). However, the ranking of fine fescue cultivars for green cover was not always in agreement with visual assessment FTC. This was primarily due to the fact that digital image analysis was not able to differentiate between weeds and desirable turf species (Karcher and Richardson, 2013). In contrast to FTC response, Slender creeping grass Shoreline and Seabreeze GT were among the cultivars with the greatest green cover during autumn in all three years and during spring in the first and third year. This was primarily due to the great amount of annual bluegrass (*Poa annua*) encroached on the plot; the FTC of these cultivars was among the poorest group during summer when annual bluegrass dies from summer stresses (Table 3.3).

Based on a preliminary result (data not shown), digital image analysis can be a useful tool to measure leaf bruising; however, more research is needed to confirm the accuracy of the method.

CONCLUSION

Response of fine fescues to abrasive wear varied based on the season during which traffic stress occurs. The FTC and green cover of fine fescue under worn condition was positively correlated to those parameters under non-worn condition. Cultivar differences during spring wear were less evident than summer but greater than autumn wear. However, due to the high disease pressure and heat stress during summer, screening for wear tolerant fine fescues is more effective during spring when these confounding factors are minimal. Cultivars with greater wear tolerance can still be vulnerable to severe leaf bruising. Leaf bruising response of fine fescue to abrasive wear is complicated by the fact that responses varied with season; thus, evaluation of leaf bruising resistant cultivars needs to be conducted in the summer and autumn.

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Table 3.1 Coefficient of correlation between non-worn and worn turf for fullness of cover, and green cover in each season of evaluation during a three-year assessment of fine fescues seeded in September 2012 a loam in North Brunswick, NJ.

	Year 1¶			Year 2‡			Year 3		
	Autumn	Spring	Summer	Autumn	Spring	Summer	Autumn	Spring	Summer
	---------- coefficient of correlation ----------								
Fullness of turf canopy	0.79***	0.74***	0.47**	0.52***	0.57***	0.61***	0.58***	0.56***	0.65***
Green cover	ns	0.35*	0.48**	0.51***	0.66***	0.39*	0.82***	0.62***	0.56***

* Significant at $p \leq 0.05$

** Significant at $p \leq 0.01$

*** Significant at $p \leq 0.001$

§ns, non-significant

¶ Year 1 assessed from autumn 2013 to summer 2014

‡ Year 2 assessed from autumn 2014 to summer 2015

† Year 3 assessed from autumn 2015 to summer 2016

Table 3.2 Fullness of turf canopy as affected by season of wear and cultivar during a three-year assessment of fine fescues seeded in September 2012 a loam in North Brunswick, NJ.

	Year 1[¶]	Year 2[‡]	Year 3[†]
		ANOVA	
Source of variation			
Season[€]	*	**	*
Cultivar	***	***	***
Season x Cultivar	***	***	***
CV (%)	9.3	6.9	8.6
Season main effect	------------------ 1 to 100%, 100% represent full cover ------------------		
Autumn	65	78	81
Spring	72	79	81
Summer	71	73	78
LSD (0.05)	5	3	2

* Significant at $p \leq 0.05$

** Significant at $p \leq 0.01$

*** Significant at $p \leq 0.001$

[¶] Year 1 assessed from autumn 2013 to summer 2014

[‡] Year 2 assessed from autumn 2014 to summer 2015

[†] Year 3 assessed from autumn 2015 to summer 2016

[€] Abrasive wear applied with the Rutgers Wear Simulator for 8 weeks during each season

Table 3.3 Fullness of turf canopy as affected by the interaction of fine fescue cultivars and the season of evaluation during a three-year assessment of fine fescues seeded in September 2012loam in North Brunswick, NJ.

	Year 1[¶]			Year 2[‡]			Year 3[†]		
	Autumn	Spring	Summer	Autumn	Spring	Summer	Autumn	Spring	Summer
Cultivar	------------------------- 0 to 100, 100 represent full turf cover -------------------------								
Beacon [HDf]	78	76	83	84	94	85	88	88	91
Blueray [HDf]	81	75	78	86	93	84	88	88	93
Quatro [SH]	66	76	80	83	89	80	84	88	94
Radar [CH]	83	75	79	75	86	78	80	88	91
Culumbra II [CH]	63	73	73	74	76	75	78	83	84
Marvel [ST]	74	79	74	80	70	71	83	66	61
Garnet [ST]	61	70	70	75	70	63	78	80	70
Shoreline [SL]	59	74	64	75	78	66	78	78	65
Aurora Gold [HD]	41	58	60	76	71	73	81	78	83
Seabreeze GT [SL]	41	60	48	68	66	59	71	73	46
LSD (0.05) row		10			8			10	
LSD (0.05) column		8			6			8	

[¶] Year 1 assessed from autumn 2013 to summer 2014
[‡] Year 2 assessed from autumn 2014 to summer 2015
[†] Year 3 assessed from autumn 2015 to summer 2016
[f] Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 3.4 Leaf bruising as affected by season of wear and cultivar during a three-year assessment of fine fescues seeded in September 2012 a loam in North Brunswick, NJ.

	Year 1¶	Year 2‡	Year 3†
		ANOVA	
Source of variation			
Season€	***	**	***
Cultivar	***	***	***
Season x Cultivar	***	***	***
CV (%)	13.7	15.4	13.1
Season of Wear	-----------1 to 9, 9 represent no bruising -----------		
Autumn	4.0	4.5	4.4
Spring	8.1	5.9	8.3
Summer	5.8	4.5	4.2
LSD (0.05)	0.3	0.8	0.6

* Significant at $p \leq 0.05$
** Significant at $p \leq 0.01$
*** Significant at $p \leq 0.001$
¶ Year 1 assessed from autumn 2013 to summer 2014
‡ Year 2 assessed from autumn 2014 to summer 2015
† Year 3 assessed from autumn 2015 to summer 2016
€ Abrasive wear applied with the Rutgers Wear Simulator for 8 weeks during each season

Table 3.5 Leaf bruising as affected by the interaction of fine fescue cultivars and the season of wear during a three-year assessment of fine fescues seeded in September 2012 a loam in North Brunswick, NJ.

Cultivar	Year 1¶ Autumn	Year 1¶ Spring	Year 1¶ Summer	Year 2‡ Autumn	Year 2‡ Spring	Year 2‡ Summer	Year 3† Autumn	Year 3† Spring	Year 3† Summer
	------------------------------ 1 to 9, 9 represent no bruising ------------------------------								
Blueray [BL x HDf]	4.3	8.5	5.5	6.5	7.3	5.4	5.3	8.8	5.3
Beacon [HD]	3.3	8.8	6.5	6.3	7.0	6.0	4.0	8.8	6.0
Aurora Gold [HD]	4.5	7.3	7.0	5.3	6.3	5.8	5.8	7.5	5.0
Quatro [SH]	6.8	7.8	5.5	7.0	5.3	5.8	6.5	6.3	3.5
Shoreline [SL]	3.8	8.3	6.8	2.5	5.3	5.0	3.5	8.8	5.3
Garnet [ST]	4.5	7.8	5.8	5.3	5.0	3.8	5.5	8.3	1.8
Seabreeze GT [SL]	4.0	8.8	5.8	3.3	5.5	4.5	2.3	8.3	4.5
Marvel [ST]	3.3	8.3	3.8	5.3	5.0	3.3	5.5	8.8	2.5
Radar [CH]	3.0	7.8	7.0	1.3	7.0	4.3	1.8	8.8	4.3
Culumbra II [CH]	2.5	7.5	4.5	2.3	5.5	4.0	4.0	8.8	4.3
LSD (0.05) row		1.0			1.1			1.0	
LSD (0.05) column		1.0			0.9			0.9	

¶ Year 1 assessed from autumn 2013 to summer 2014

‡ Year 2 assessed from autumn 2014 to summer 2015

† Year 3 assessed from autumn 2015 to summer 2016

f Fine fescues species designated by SH = sheep; HD = hard; CH = Chewings; ST = strong creeping red; SL = slender creeping red

Table 3.6 Green cover as affected by season of wear and cultivar during a three-year assessment of fine fescues seeded in September 2012 a loam in North Brunswick, NJ.

	Year 1[¶]	Year 2[‡]	Year 3[†]
		ANOVA	
Source of variation			
Season[€]	***	***	***
Cultivar	***	***	***
Season x Cultivar	*	***	***
CV (%)	16.9	8.5	7.8
Season main effect	--------- 1 to 100%, 100% represent full green cover ---------		
Autumn	36	71	62
Spring	56	53	63
Summer	35	23	31
LSD (0.05)	3	6	7

* Significant at $p \leq 0.05$
** Significant at $p \leq 0.01$
*** Significant at $p \leq 0.001$
[¶] Year 1 assessed from autumn 2013 to summer 2014
[‡] Year 2 assessed from autumn 2014 to summer 2015
[†] Year 3 assessed from autumn 2015 to summer 2016
[€] Abrasive wear applied with the Rutgers Wear Simulator for 8 weeks during each season

Table 3.7 Green cover as affected by the interaction of fine fescue cultivars and the season of wear during a three-year assessment of fine fescues seeded in September 2012 a loam in North Brunswick, NJ.

	Year 1¶			Year 2‡			Year 3		
	Autumn	Spring	Summer	Autumn	Spring	Summer	Autumn	Spring	Summer
Cultivar	------------------------- 0 to 100, 100 represent full green cover -------------------------								
Beacon [HDf]	56	74	67	89	80	48	68	67	41
Blueray [HD]	54	68	56	89	80	47	71	64	40
Quatro [SH]	55	70	53	90	74	44	72	52	35
Radar [CH]	50	80	53	75	78	44	60	72	31
Aurora Gold [HD]	49	71	59	79	67	45	69	58	38
Seabreeze GT [SL]	55	75	47	88	69	38	73	72	8
Culumbra II [CH]	45	69	44	75	76	42	61	69	30
Shoreline [SL]	48	75	39	87	66	33	72	72	18
Marvel [ST]	55	72	54	76	56	47	63	51	33
Garnet [ST]	46	67	42	77	61	40	58	58	32
LSD (0.05) row		8			7			7	
LSD (0.05) column		7			5			5	

¶ Year 1 assessed from autumn 2013 to summer 2014

‡ Year 2 assessed from autumn 2014 to summer 2015

† Year 3 assessed from autumn 2015 to summer 2016

f Fine fescues species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

CHAPTER 4 Cell Wall Composition of Three Fine Fescue Species Under Four of Nitrogen Fertilization Levels

ABSTRACT

Cell wall constituents have been reported to associate with wear tolerance of turfgrass. Research on forage grass indicated significant nitrogen (N) fertilization effects on cell wall composition and feed digestibility; however, the effect of N fertilization varied with species. The objective of this 2-year field study was to assess the cell wall composition of three fine fescue species (*Festuca spp.*) in response to four levels of N fertilization: 0, 49, 98, and 146 kg ha^{-1} $year^{-1}$. Fine fescue cultivars were seeded in September 2012 on a loam at Hort Farm 2 in North Brunswick, NJ. Fertilizer was applied as ammonium nitrate with four split applicaitons per year at rates of 0, 12.3, 24.5, and 36.5 kg ha^{-1}per application,respectively. Turf color and turf quality was visually assessed monthly along with chlorophyll index (measured with FieldScout CM1000) and normalized difference vegetation index (NDVI; measured with a multispectral radiometer). Verdure samples were collected three times a year to determine verdure biomass and concentrations of total N, total carbon (C), and concentration of cell wall constituents including total cell wall content (TCW), lignocellulose, hemicellulose, lignin, and cellulose. N fertilization increased the total N concentration in the verdure but did not alter the cell wall composition. Hard fescue ‘Beacon’ had the highest concentration in all cell wall constituents followed by Chewings fescue ‘Rushmore’; strong creeping red fescue ‘Garnet’ was lowest in all cell wall constituents. Increased N fertilization produced more succulent and hydrated turf but did not affect dry verdure biomass of fine fescues. Better turf quality, darker green color, greater chlorophyll content, and greater NDVI values were observed as N

fertilization level increased. However, when summer patch (caused by *Magnaporthe poae*) disease was active, better turf quality and darker green color were observed on fine fescues receiving 0 to 49 kg N ha^{-1} $year^{-1}$. The N ferilitzation had no effect on cell wall composition of fine fusce in this study which suggested that cell wall constituents have the potential to be used as a stbale trait for traffic tolerant cultivar selection.

INTRODUCTION

Fine fescues (*Festuca* spp.) are a group of cool-season turfgrass species that requires less water and fertilizer compared to other commonly used cool-season grasses (Bonos and Huff, 2013). However, these species are not utilized to the same extent as other species partially due to their poor traffic tolerance and recuperative ability. Improvement in traffic tolerance of fine fescues will enable greater use of these species by the turf industry.

Numerous studies indicated that cell wall constituents were important in determining wear tolerance of turfgrass (Shearman and Beard, 1975b; Canaway, 1978; Canaway, 1981; Bourgoun et al. 1985; Kilmartin, 1994; Trenholm et al. 2000; Brosnan et al., 2005; Den Haan et al., 2009; Dowgiewicz et al., 2011). Shearman and Beard (1975) observed improved wear tolerance of creeping bentgrass (*Agrostis stolonifera*) with increased nitrogen (N) and potassium (K) application. They also reported increased concentrations of total cell wall (TCW), lignocellulose, cellulose, and lignin content with increasing N level.

Effect of N fertilization on concentration of cell wall constituents and feed digestibility has been well recorded in forage grass species. Studies conducted on Congo grass (*Brachiaria ruziziensis*), African bristlegrass (*Setaria sphacelate*) Italian ryegrass (*Festuca perennis*), perennial ryegrass (*Lolium perenne*), and cocksfoot (*Dactylis glomerata*) reported that the concentration of cell wall constituents increased by increasing N level (Deinum and Dirven, 1976; Wilman and Wright, 1978). A more recent study also found increasing N level resulted in a small but statistically significant increase of TCW, cellulose, and lignin concentrations in switchgrass (*Phalaris virgatum*) and reed canary grass (*Phalaris arundinacea*) (Allison et al., 2012). However, negative correlations between N fertilization and concentration of cell wall constituents were also reported in *Miscanthus* (Hodgson et al., 2010).

These results suggest the effect of N fertilization on plant cell wall composition might vary with species. There have been limited studies on how N fertilizers may alter cell wall composition in fine fescue species. Thus, the objective of this study was to determine the effects of N fertilization on N content, biomass, and cell wall composition within the verdure of three fine fescue species.

MATERIALS AND METHODS

Site Description and Maintenance

Fine fescue cultivars were seeded into 1.8- x 3.6-m plots in September 2012 on a Nixon loam (fine-loamy, mixed, mesic Typic Hapludults) at Hort Farm 2 in North Brunswick, NJ. The turf plots were grow-in with annual N rates of 70.8, 86.4, and 42.0 kg ha^{-1} in 2012, 2013, and 2014, respectively. N was applied as ammonium sulfate, and urea and K were applied as sulfate of potash with 16-0-8 granular N-P_2O_5-K_2O fertilizer. Soil testing indicated that soil pH ranged from 6.0 to 6.7 and soil P and K were no less than 134 and 165 mg kg^{-1}, respectively, from 2014 to 2017. The trial was mowed at 6.4 cm once a week from April to November, except during periods of high air temperature and dry soil when mowing was suspended to avoid bruising damage from tires. Irrigation was applied to avoid severe drought stress.

Summer patch (caused by *Magnaporthiopsis poae*) and dollar spot (caused by *Clarireedia jacksonii*) was suppressed by fluoxastrobin applied at a rate of 0.55 kg a.i. ha^{-1} on 15 June, 12 July and 2 Aug. 2013, 14 May, 11 June, 8 July and 1 Aug. 2014, 19 May and 15 June 2015 in rotation with pyraclostrobin applied at 0.56 kg a.i. ha^{-1} on 6 July, 3 and 18 Aug., 17 Nov. 2015, 23 May, 17 June, 14 July, 12 Aug., 2 Sep.

and 31 Oct. 2016. Pythium was controlled with cyazofamid applied at 2.75 kg a.i. ha^{-1} on 12 and 26 July 2016. Trifloxystrobin combined with triadimefon was applied to control pink snow mold (caused by *Michrodocium nivale*) at 0.61 kg a.i. ha^{-1} on 21 Dec. 2015. Leaf spot (caused by *Drechslera dictyoides*) was suppressed by penthiopyrad applied at 1.53 kg a.i. ha^{-1} on 12 May and 3 June 2016.

Sod webworm, chinch bugs and white grubs were controlled using chlorantraniliprole applied at 0.06 kg a.i. ha^{-1} and 0.18 kg a.i. ha^{-1} on 29 Aug. 2013 and 26 July 2014, respectively; Imidacloprid applied at 0.55 kg a.i. ha^{-1} and 0.61 kg a.i. ha^{-1} on 11 June 2015; and Clothianidin applied at 0.88 kg a.i. ha^{-1} on 4 Oct. 2016.

Broadleaf weeds were controlled by dimethylamine salt of dicamba and 2,4-Dichlorophenoxyacetic acid applied at 0.28 and 0.54 kg a.i. ha^{-1}, respectively, on 11 April 2013; 2,4-Dichlorophenoxyacetic acid and triclopyr acetic acid applied at 0.54 and 1.12 kg a.i. ha^{-1}, respectively, on 19 April 2014; carfentrazone-ethyl applied at the rate of 0.03 kg a.i. ha^{-1}, 2,4-Dichlorophenoxyacetic acid at the rate of 1.05 kg a.i. ha^{-1}, mecoprop applied at the rate of 0.33 kg a.i. ha^{-1}, and dicamba applied at the rate of 0.10 kg a.i. ha^{-1} on 31 July 2015. Clopyralid was used to control crabgrass at a rate of 0.28 kg a.i. ha^{-1} on 15 April 2014 and 17 April.

Experimental Design

This trial was a 3 x 4 factorial arranged in a split-plot design with 3 replications. The main plot factor consisted of three fine fescue species: hard fescue (*F. brevipila* 'Beacon'), strong creeping red fescue (*F. rubra* ssp. *Rubra* 'Garnet'), and Chewings fescue (*F. rubra* ssp. *commutata* 'Rushmore'). The subplot factor was four annual N levels: 0, 49, 98, and 146 kg ha^{-1} $year^{-1}$. N fertilizer was applied as ammonium nitrate four times per year at rates of 0, 12.3, 24.5, and 36.5 kg ha^{-1} on 12

May 2015 and 16 May 2016, 9 June 2015 and 2016, 25 August 2015 and 22 August 2016; and 22 September 2015 and 19 September 2016.

Data Collection and Analysis

Visual ratings of turf quality (1- 9; 9 = best quality) and color (1- 9; 9 = darkest green) along with chlorophyll index measured with a FieldScout CM1000 chlorophyll meter (Spectrum Technologies Inc., Aurora, IL) were recorded monthly from July to October in 2015 and 2016. Normalized difference vegetation index (NDVI) was measured by a multispectral radiometer (CROPSCAN Inc., Rochester, MN) when treatment differences were apparent. Summer patch damage (1-9; 9 = no damage) was rated when disease symptoms were present.

Verdure samples were collected using a grass shear (GARDENA Canada LTD., Brampton, ON, Canada) before the first N fertilizer application on 11 May 2015 and 16 May 2016; 2 weeks after the second N fertilizer application on 23 June 2015 and 20 June 2016; and two weeks after the fourth N fertilizer application on 15 October 2015 and five weeks after the fourth N fertilizer application on 3 November 2016. All samples were weighed during collection, and dried at 70 °C for 72 hours, and weighed again. Leaf moisture, fresh biomass, and dry biomass were calculated using the equations:

$$leaf\ moisture\ (\%) = \frac{100 \times (fresh\ weight - dry\ weight)}{fresh\ weight}$$

$$fresh\ biomass\ (g\ m^{-2}) = \frac{fresh\ weight}{sampling\ area}$$

$$dry\ biomass\ (g\ m^{-2}) = \frac{dry\ weight}{sampling\ area}$$

Dry samples were ground using Wiley Mill (Thomas Scientific, Swedesboro, NJ) to pass a 1-mm sieve. Ground samples were subjected to fiber analysis according to the methods described by Goering and Van Soest (1970) to determine the concentration of total cell wall (TCW), lignocellulose, hemicellulose, lignin, and cellulose. The neutral detergent fiber (NDF) procedure was used to determine TCW concentration on a dry weight basis. The acid detergent fiber (ADF) was used to determine lignocellulose concentration. The difference between the quantity of NDF and ADF was used to estimate the hemicellulose concentration. The acid detergent lignin (ADL) was used to determine the lignin concentration, and the difference between the quantity of ADF and ADL was used to estimate cellulose concentration.

Filter bags and ANKOM A200 Fiber Analyzer (ANKOM Technology, Macedon, NY) were used for both NDF and ADF procedures. Approximately 0.5-g of dried ground samples were weighed and heat-sealed in filter bags. Bags/samples were placed bag suspender trays with an empty filter bag that serves a negative control to detect leaking of samples. When performing the NDF procedure, 2000-ml neutral detergent solution, 20-g of sodium sulfite, and 4-ml of alpha-amylase were added to the fiber analyzer vessel and heated to 100 °C. After agitated in neutral detergent solution at 100 °C for 75 minutes, bags/samples were rinsed with hot water (70-90 °C) water and 4-ml of alpha-amylase three times for 5 minutes each time. After rinsing, bags/samples were soaked in sufficient acetone in a beaker to remove moisture and then oven-dried at 102 °C for 4 hours. After performing NDF determination, bags/samples were placed back to the fiber analyzer vessel and agitated in acid detergent solution at 100 °C for 60 minutes followed the same rinsing (without alpha-amylase) and drying procedure. After performing ADF determination, bags/samples were placed into 3000-ml beaker with sufficient quantity (approximately 250-ml) of 72% H_2SO_4 to cover bags/samples. A 2000-ml beaker was used to keep bags/samples submerged inside the 3000-ml beaker. Bags/samples were agitated every 30 minutes by pushing and lifting 2000-ml beaker up and down approximately 30 times. After 3 hours, bags/samples were removed from H_2SO_4 and rinsed with hot water (70-90 °C) to remove all acid.

Calculations:

$$total\ cell\ wall\ (NDF;\%)=\frac{100\times(W_3-(W_1\times C_1))}{W_2}$$

$$lignocellulose\ (ADF;\%)=\frac{100\times(W_4-(W_1\times C_2))}{W_2}$$

$$lignin\ (ADL;\%)=\frac{100\times(W_5-(W_1\times C_3))}{W_2}$$

$$hemicellulose\ (\%)=total\ cell\ wall-lignocellulose$$

$$cellulose\ (\%)=lignocellulose-lignin$$

where:

W_3=*dried weight of bag with sample after NDF extraction process*

$$C_1=\frac{blank\ bag\ weight\ after\ NDF\ extraction\ process}{original\ blank\ bag\ weight}$$

W_4=*dried weight of bag with sample after ADF extraction process*

$$C_2=\frac{blank\ bag\ weight\ after\ ADF\ extraction\ process}{original\ blank\ bag\ weight}$$

W_5=*dried weight of bag with sample after ADF extraction process*

$$C_3=\frac{blank\ bag\ weight\ after\ ADL\ extraction\ process}{original\ blank\ bag\ weight}$$

Total nitrogen (N) concentration, total carbon (C) concentration, and C:N ratio were measured using an Elementar Vario Max analyzer (Vario MAX cube, Hanau, Germany) according to the Dumas combustion methods described by Kirsten (1983). Approximately 1-gram of sample was used during the process.

All data were analyzed using a 3 x 4 factorial arranged in a split-plot design with four replications. Statistical analyses were carried out using the Statistical

Analysis System (SAS) software package (v. 9.4; SAS Institute), and data were subjected to analysis of variance (ANOVA) using the GLM procedure for a split-plot design. Statistically significant main effects and interaction means were separated using Fisher's protected least significant difference test at the 0.05 probability level.

RESULTS AND DISCUSSION

Total N in Verdure

As expected, verdure N concentration was influenced by N fertilization main effects (Table 4.1). Verdure N concentration increase in a linear fashion with increasing N fertilization. Species main effect also had a significant impact on verdure N concentration; Chewings fescue and strong creeping red fescue had higher verdure N concentration than hard fescue (Table 4.1).

Leaf Moisture and Verdure Biomass

Leaf moisture (Table 4.2) and fresh verdure biomass (Table 4.3) increased with increasing N fertilization. The results confirm that N fertilizer promotes plant growth and result in a more succulent and hydrated turf (Shearman and Beard, 1975). The species main effect on leaf moisture and fresh verdure biomass was also significant. The relative rankings for leaf moisture from high to low were: Chewings > strong creeping red > hard (Table 4.2). The relative rankings for fresh biomass from high to low were hard > Chewings > strong creeping red (Table 4.3). Verdure dry biomass was only influenced by species main effect but not N fertilization (Table 4.4). The relative rankings of dry verdure biomass were the same as the rakings for fresh verdure biomass.

Ranges for sufficient tissue N concentrations for turfgrass responses have been previously defined in the literature. Tissue N concentrations in healthy cool-season turf and pasture grasses were reported to be from 24 to 83 g kg^{-1} for creeping bentgrass (*Agrostis stolonifera* L.), 34 to 47 g kg^{-1} for tall fescue, 33 to 51 g kg^{-1} for perennial ryegrass (*Lolium perenne* L.), and 25 to 51 g kg^{-1} for Kentucky bluegrass (Mills and Jones, 1996). There has been a lack of studies to determine the sufficiency range of N concentration for fine fescues. Total N concentration in this study ranged from 12.9 g kg^{-1} to 23.9 g kg^{-1}, which is below those ranges defined for other cool-season species. A broader range of N levels needs to be investigated to define the minimum and critical N concentration in plant tissues to guide N fertilization on fine fescue turf better.

Turf Response to N level

N fertilization main effect was significant on eight out of nine rating dates for turf quality (Table 4.5) and six out of nine rating dates for turf color (Table 4.6). Turf quality and turf color were also influenced by the summer patch (*Magnaporthiopsis poae*) disease in August 2016 (Table 4.7). N fertilization produced improved turf quality and darker color than the untreated control (Tables 4.5 and 4.6). Plots received 146 kg N ha^{-1} $year^{-1}$ exhibited darkest turf color (Table 4.6); however, there was no significant difference for turf quality among N levels (Table 4.5). Turf quality and turf color started to decline after August 2016 due to the summer patch outbreak. Plots received 0 and 49 kg N ha^{-1} $year^{-1}$ were less affected by summer patch disease (Table 4.7) and exhibited better turf quality (Table 4.3) than high than plots received 98 and 146 kg N ha^{-1} $year^{-1}$. The species main effect was significant on turf quality and turf color while the rankings depended on the summer patch disease pressure. Strong creeping red fescue had the most severe summer patch disease infection among three species (Table 4.7). Strong creeping red fescue was able to produce turf quality either better or similar to Chewings and hard fescue when disease pressure was low;

however, it had the poorest turf quality after infected by summer patch in August 2016 (Table 4.3).

Similar to quality and color response, chlorophyll concentration was also influenced by summer patch disease. Significant N level effect was observed in eight out of nine measuring dates except August 2016 when summer patch symptom was evident (Table 4.8). Plots received 98 and 146 kg N ha^{-1} $year^{-1}$ had greater chlorophyll concentration than the plots received no N fertilization from July 2015 to June 2016 when pressure was low. Under high disease pressure, however, plots received 0 and 49 kg N ha^{-1} $year^{-1}$ had higher chlorophyll concentration than Plots received 98 and 146 kg N ha^{-1} $year^{-1}$ in September and October of 2016 (Table 4.8). Significant species effect was observed in four out of nine measuring dates. Strong creeping red and Chewings fescue had greater chlorophyll concentration than hard fescue from August 2015 to June 2016, while the opposite result was observed in August 2016 due to summer patch damage summer patch pressure (Table 4.8).

N fertilization effect on NDVI was significant on all the measuring dates except August 2016 due to summer patch damage (Table 4.9). Plots received N fertilization exhibited greater NDVI than the plots without N fertilization. Among different N levels, plots received 146 kg N ha^{-1} $year^{-1}$ showed greater NDVI than plot received 49 kg N ha^{-1} $year^{-1}$ on three out of five measuring dates. Significant species main effect was observed on two measuring dates; strong creeping red and Chewings fescue had greater NDVI than hard fescue (Table 4.9).

Positive correlation between turf quality, turf color, and chlorophyll concentration with N fertilization was reported on cool-season grasses including perennial ryegrass (Flowers et al., 2010;), Kentucky bluegrass (Geng et al., 2015; Guillard et al., 2016), tall fescues (Geng et al., 2015), and creeping bentgrass (Kruse et al., 2006; Zhu et al., 2012). Skogley and Ledeboer (1968) reported poor fine fescue turf covers at 49 kg N ha^{-1} yr^{-1} but satisfactory performances at 98 and 146 kg N ha^{-1} yr^{-1}. Better turf quality was observed on Chewings fescue and slender creeping red fescue while strong creeping red fescue had the poorest turf quality in response to increasing fertilizer levels. Nitrogen use efficiency (NUE) was reported to be different among fine fescue species (Bourgoin 1997). Turf quality response of Chewings fescue and slender creeping red fescue to N fertilization was greater than strong creeping (Skogley and Ledeboer, 1968). Calvache et al. (2017) found improved turf quality and color of fine fescue turf with increasing N; the author also indicated a diminishing effect of N fertilization as N increased to 150 kg ha^{-1} yr^{-1}. The range of N fertilization tested in this study did not seem to reach the N response plateau; however, N fertilization appeared to influence the disease and affected the quality and color of fine fescues. The effects of N fertilization on disease tolerance in fine fescue require further examination.

Cell Wall Composition in Verdure

There was no N fertilization on verdure C concentration. The difference among fine fescue species was only significant in October 2015; Chewings fescue had greater verdure C concentration than hard fescue and strong creeping red fescue (Table 4.10).

Cell wall composition was predominantly determined by species main effect; N fertilization did not alter the cell wall composition of fine fescues (Table 4.11 to 4.15). The difference of TCW among the species was significant in all sampling dates, and the rankings of fine fescues species remained the same. Hard fescue had the highest TCW content, ranged from 65.6% to 68.3%, followed by Chewings fescue, ranged from 62.6% to 65.9%; strong creeping red fescue had the lowest TCW content ranged from 58.7% to 63.1% (Table 4.11). Similar rankings were observed in lignocellulose and hemicellulose content. Hard and Chewings had similar lignocellulose and hemicellulose content and both of which were greater than strong creeping red fescue (Table 4.12 and Table 4.13). The lignin content in hard fescue was the highest followed by Chewings fescue; strong creeping red fescue had the lowest lignin content among three species (Table 4.14). More variability existed in cellulose content compared to total cell wall constituents; significant species main effect was observed on three out of six sampling dates; hard and Chewings fescue had similar cellulose content, which was greater than that of strong creeping red fescue (Table 4.15).

The effect of N fertilization on cell wall composition has been investigated in forage grass, but the results varied by species. The result in this study confirms the findings of Blaser (2019), who reported improved protein and soluble carbohydrates content of perennial forage grass with added N fertilizer, while N fertilization did not change the cellulose or crude fiber content and lignification. Valk et al. (1996) also found N fertilization has no effect on TCW concentration of forage type perennial ryegrass (*Lolium perenne*), while elevated N level increased crude protein content and decreased the content of dry matter.

The discrepant results among these studies may occur due to the difference in management practices, environmental factors, sample preparation, and stage of growth, which could affect the cell wall composition. Wilman and Wright (1978) proposed that the change of cell wall composition resulted from N fertilization was greater at earlier regrowth stages, and the differences disappeared almost completely at 6–8 weeks of regrowth. The author concluded that N fertilization increased the growth of new leaf tissues, which are low in cell wall content. In this study, verdure samples were collected two weeks after N fertilization when the effect of N fertilization started to fade and the difference might not be evident enough to detect. In addition, the verdure samples collected from this study were composed of leaf blades and leaf sheath. It is possible that the more lignified leaf sheath reduced the effect of leafy growth after N fertilization and resulted in a relatively stable cell wall composition. However, the harvest time effect needs to be further investigated to either confirm or deny the finding in this study.

It is also important to note the range of N fertilization levels tested in this study was relatively narrow (0, 49, 98, 146 kg ha^{-2}) compared to other studies. Hodgson et al. (2010) who reported cell wall content of *Miscanthus* decreased with increasing N level (0, 50, 100, 150, 200, or 250 kg ha^{-2}). The author observed the highest biomass and protein content while the lowest soluble carbohydrates and fiber contents with the highest N level. It is possible that the effect of N on cell wall composition was not observed in this study because of the narrow range of N levels tested.

CONCLUSION

In this study, N fertilization increases the total N concentration in the verdure, and produced more succulent and hydrated turf; however, increased N fertilization did not affect dry verdure biomass of fine fescues. The response of turf quality and turf color to N fertilization was influenced by summer patch disease. Improved turf quality, darker turf color, and greater chlorophyll content and NDVI were observed with additional N application under low disease pressure was low. However, fine fescues received 0 to 49 kg N ha^{-1} $year^{-1}$ were less susceptible to summer patch disease; thus, exhibited better turf quality when disease pressure was high. The effects of N fertilization on the fine fescues quality and disease tolerance requires further examination.

N fertilization did not alter the total C concentration or cell wall composition in the verdure of fine fescues. Cell wall composition was predominantly determined by fine fescue species. Differences among three fine fescue species were significant and the ranking remained the same throughout the entire study. Hard fescue had the greatest content in all cell wall constituents, including TCW, lignocellulose, hemicellulose, lignin, and cellulose, while Chewings fescues were intermediate and strong creeping red fescue had the lowest cell wall contents.

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Table 4.1 Total N concentration of verdure as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
			ANOVA			
Source of variation						
Species	**	***	**	***	***	***
N Fertilization	ns	***	***	***	***	***
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	---------------------- N (%) ----------------------					
Hard (Beacon)	13.2	17.6	21.4	11.3	13.0	18.5
Strong creeping red (Garnet)	15.9	22.0	27.3	14.1	16.1	25.6
Chewings (Rushmore)	17.7	22.1	25.8	15.6	16.6	23.0
LSD $_{(0.05)}$	1.5	0.8	1.9	0.9	0.7	0.7
Annual N Fertilization						
0 kg ha^{-1}	15.8	18.1	20.4	12.8	12.9	20.6
49 kg ha^{-1}	15.4	19.7	24.1	13.3	14.6	22.0
98 kg ha^{-1}	15.6	21.6	26.1	13.8	15.9	22.9
146 kg ha^{-1}	15.6	22.8	28.7	14.6	17.6	23.9
LSD $_{(0.05)}$	ns	1.0	1.8	0.7	1.1	1.0

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.2 Leaf moisture as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
			ANOVA			
Source of variation						
Species	ns	ns	*	**	*	ns
N Fertilization	ns	***	*	*	***	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	------------------ leaf moisture (%) ------------------					
Hard (Beacon)	56.4	44.7	61.0	59.9	58.5	67.9
Strong creeping red (Garnet)	55.9	41.6	67.6	60.0	62.2	69.0
Chewings (Rushmore)	57.5	44.3	68.1	66.8	63.3	70.3
LSD $_{(0.05)}$	ns	ns	4.5	3.2	2.4	ns
Annual N Fertilization						
0 kg ha^{-1}	57.6	38.7	61.9	59.1	57.1	70.3
49 kg ha^{-1}	56.0	42.6	64.3	61.7	60.7	69.9
98 kg ha^{-1}	55.6	45.6	65.6	64.2	62.5	67.7
146 kg ha^{-1}	57.2	47.3	70.5	63.9	65.0	68.4
LSD $_{(0.05)}$	ns	2.5	5.9	3.3	2.4	ns

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.3 Fresh verdure biomass as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
			ANOVA			
Source of variation						
Species	**	*	ns	*	ns	*
N Fertilization	ns	*	ns	ns	***	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	----------------- fresh biomass (kg m^{-2}) -----------------					
Hard (Beacon)	0.85	1.04	0.87	1.47	1.45	1.85
Strong creeping red (Garnet)	0.65	0.83	0.79	1.08	1.21	0.80
Chewings (Rushmore)	0.69	0.92	0.90	1.09	1.28	1.30
LSD $_{(0.05)}$	0.06	0.17	ns	0.24	ns	0.77
Annual N Fertilization						
0 kg ha^{-1}	0.73	0.84	0.83	1.15	1.06	1.33
49 kg ha^{-1}	0.71	0.92	0.81	1.18	1.26	1.45
98 kg ha^{-1}	0.70	0.98	0.86	1.24	1.37	2.22
146 kg ha^{-1}	0.77	0.99	0.91	1.28	1.56	1.28
LSD $_{(0.05)}$	ns	0.10	ns	ns	0.02	ns

*Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ns, non-significant

Table 4.4 Dry verdure biomass as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
	ANOVA					
Source of variation						
Species	*	*	ns	**	*	*
N Fertilization	ns	ns	ns	ns	ns	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	---------------- dry biomass (kg m^{-2}) ----------------					
Hard (Beacon)	0.37	0.35	0.35	0.59	0.60	0.59
Strong creeping red (Garnet)	0.28	0.27	0.26	0.43	0.45	0.24
Chewings (Rushmore)	0.29	0.28	0.29	0.36	0.46	0.38
LSD $_{(0.05)}$	0.05	0.05	ns	0.07	0.12	0.22
Annual N Fertilization						
0 kg ha^{-1}	0.31	0.30	0.32	0.47	0.46	0.39
49 kg ha^{-1}	0.31	0.31	0.29	0.46	0.50	0.43
98 kg ha^{-1}	0.31	0.30	0.30	0.44	0.52	0.38
146 kg ha^{-1}	0.33	0.30	0.27	0.46	0.55	0.40
LSD $_{(0.05)}$	ns	ns	ns	ns	ns	ns

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.5 Turf quality as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015				2016				
	July	Aug.	Sept.	Oct.	June	July	Aug.	Sept.	Oct.
					ANOVA				
Source of variation									
Species	ns	ns	**	ns	ns	ns	ns	ns	*
N Fertilization	*	*	**	***	***	**	ns	**	*
Species x N Fertilization	ns	ns	ns	ns	ns	ns	ns	*	ns
Species (Cultivar)	------------- turf quality (1 to 9; 9 = best) -------------								
Hard (Beacon)	8.5	6.7	6.0	6.9	7.5	7.9	5.8	5.1	5.3
Strong creeping red (Garnet)	8.8	6.8	8.1	8.6	8.1	8.1	5.7	3.9	3.8
Chewings (Rushmore)	8.8	6.9	7.5	8.3	8.1	7.6	5.5	4.6	4.3
LSD $_{(0.05)}$	ns	ns	0.8	ns	ns	ns	ns	0.8	0.8
Annual N Fertilization									
0 kg ha^{-1}	8.3	5.6	5.4	6.6	6.1	6.6	5.6	5.2	5.8
49 kg ha^{-1}	8.6	7.3	7.3	8.1	8.0	8.0	6.0	5.9	5.6
98 kg ha^{-1}	8.8	6.9	7.6	8.4	8.6	8.4	5.9	4.4	3.6
146 kg ha^{-1}	9.0	7.3	8.4	8.6	8.9	8.4	5.1	2.6	3.1
LSD $_{(0.05)}$	0.4	1.4	1.5	0.8	0.9	1.0	ns	1.7	2.0

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.6 Turf color as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015				2016				
	July	Aug.	Sept.	Oct.	June	July	Aug.	Sept.	Oct.
					ANOVA				
Source of variation									
Species	ns	ns	**	ns	ns	*	*	ns	ns
N Fertilization	***	**	**	***	***	*	ns	ns	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns	ns	ns	ns
Species (Cultivar)	------------ turf color (1 to 9; 9 = darkest green) ------------								
Hard (Beacon)	8.1	6.4	6.6	6.7	6.8	7.4	6.0	8.0	7.5
Strong creeping red (Garnet)	8.2	7.3	7.9	7.9	7.3	7.8	5.6	8.3	7.6
Chewings (Rushmore)	8.0	6.9	7.8	8.0	7.1	7.5	5.6	8.0	7.6
LSD $_{(0.05)}$	ns	ns	0.5	ns	ns	0.3	0.3	ns	ns
Annual N Fertilization									
0 kg ha^{-1}	7.3	5.3	5.6	5.6	5.1	6.9	5.9	8.1	7.6
49 kg ha^{-1}	7.9	7.2	7.6	7.8	6.8	7.2	6.0	8.1	7.7
98 kg ha^{-1}	8.2	7.2	7.9	8.3	7.7	7.9	5.7	8.3	7.3
146 kg ha^{-1}	9.0	7.7	8.7	8.4	8.8	8.3	5.3	7.9	7.7
LSD $_{(0.05)}$	0.4	1.3	0.6	0.5	0.7	0.9	ns	ns	ns

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.7 Summer patch damage as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2016	2016
	Aug.	Sept.
	ANOVA	
Species	ns	*
N Fertilization	*	*
Species x N Fertilization	ns	ns
Species (Cultivar)	--- summer patch damage (1 to 9; 9 = no disease) ---	
Hard (Beacon)	6.1	5.2
Strong creeping red (Garnet)	5.7	3.8
Chewings (Rushmore)	5.7	4.8
LSD $_{(0.05)}$	ns	0.8
Annual N Fertilization		
0 kg ha^{-1}	6.0	4.9
49 kg ha^{-1}	6.8	5.8
98 kg ha^{-1}	5.6	4.4
146 kg ha^{-1}	4.9	3.2
LSD $_{(0.05)}$	1.8	2.1

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.8 Chlorophyll index as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015				2016				
	July	Aug.	Sept.	Oct.	June	July	Aug.	Sept.	Oct.
					ANOVA				
Source of variation									
Species	ns	*	**	ns	*	ns	*	ns	ns
N Fertilization	***	**	***	***	***	**	ns	*	*
Species x N Fertilization	ns	ns	ns	ns	ns	ns	ns	ns	ns
Species (Cultivar)	-------------------- Chlorophyll index ¶ --------------------								
Hard (Beacon)	260	235	314	328	313	236	190	292	245
Strong creeping red (Garnet)	249	247	399	341	362	254	162	263	230
Chewings (Rushmore)	251	250	406	345	353	248	163	267	235
LSD $_{(0.05)}$	ns	11	28	ns	37	ns	22	ns	ns
Annual N Fertilization									
0 kg ha^{-1}	233	214	307	283	271	227	173	307	254
49 kg ha^{-1}	245	238	371	352	332	241	177	285	254
98 kg ha^{-1}	267	246	388	345	360	258	172	254	219
146 kg ha^{-1}	267	257	425	372	408	257	165	250	219
LSD $_{(0.05)}$	13	19	30	36	30	15	ns	53	30

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant
¶ Chlorophyll index measured with FieldScout CM 1000 Chlorophyll Meter: greater number represents greater chlorophyll content

Table 4.9 Normalized difference vegetation index (NDVI) as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015		2016		
	July	Sept.	June	July	Aug.
			ANOVA		
Source of variation					
Species	ns	***	**	ns	ns
N Fertilization	**	***	***	***	ns
Species x N Fertilization	ns	ns	ns	ns	ns
Species (Cultivar)	------------------------	NDVI ¶	------------------------		
Hard (Beacon)	0.84	0.86	0.86	0.78	0.78
Strong creeping red (Garnet)	0.82	0.89	0.89	0.78	0.78
Chewings (Rushmore)	0.84	0.90	0.89	0.77	0.78
LSD $_{(0.05)}$	ns	0.01	0.01	ns	ns
Annual N Fertilization					
0 kg ha^{-1}	0.81	0.86	0.85	0.74	0.79
49 kg ha^{-1}	0.83	0.88	0.90	0.77	0.79
98 kg ha^{-1}	0.84	0.89	0.90	0.79	0.79
146 kg ha^{-1}	0.85	0.90	0.90	0.79	0.77
LSD $_{(0.05)}$	0.01	0.01	0.01	0.01	ns

* Significant at $p \le 0.05$.
** Significant at $p \le 0.01$.
*** Significant at $p \le 0.0001$.
§ ns, non-significant
¶ NDVI measured with a CROPSCAN multispectral radiometer: greater number represents greater green vegetation

Table 4.10 Total C concentration of verdure as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
			ANOVA			
Source of variation						
Species	ns	ns	**	ns	ns	ns
N Fertilization	ns	ns	ns	ns	ns	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	---------------------- total C (%) ----------------------					
Hard (Beacon)	43	44	44	43	43	42
Strong creeping red (Garnet)	42	43	43	42	42	42
Chewings (Rushmore)	43	44	48	43	43	43
LSD $_{(0.05)}$	ns	ns	2	ns	ns	ns
Annual N Fertilization						
0 kg ha^{-1}	43	44	43	43	42	42
49 kg ha^{-1}	43	43	44	42	43	43
98 kg ha^{-1}	42	44	44	43	43	43
146 kg ha^{-1}	42	43	44	43	43	43
LSD $_{(0.05)}$	ns	ns	ns	ns	ns	ns

* Significant at p≤0.05.
** Significant at p≤0.01.
*** Significant at p≤0.0001.
§ ns, non-significant

Table 4.11 Total cell wall (TCW) content of verdure as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
			ANOVA			
Source of variation						
Species	***	**	***	*	*	***
N Fertilization	ns	*	ns	ns	ns	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	---------------------- TCW (%) ----------------------					
Hard (Beacon)	68.3	67.2	69.1	65.6	66.4	67.8
Strong creeping red (Garnet)	58.7	63.1	62.9	59.7	62.9	60.5
Chewings (Rushmore)	64.5	64.9	65.9	62.6	65.6	64.5
LSD $_{(0.05)}$	2.0	1.0	2.1	3.9	2.3	1.2
Annual N Fertilization						
0 kg ha^{-1}	63.8	66.0	66.6	62.8	64.5	64.3
49 kg ha^{-1}	63.6	65.1	66.5	62.6	65.0	64.7
98 kg ha^{-1}	64.0	64.8	65.5	63.5	65.8	64.0
146 kg ha^{-1}	63.9	64.4	65.4	61.4	64.5	64.0
LSD $_{(0.05)}$	ns	1.1	ns	ns	ns	ns

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
[§] ns, non-significant

Table 4.12 Lignocellulose content of verdure as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
	ANOVA					
Source of variation						
Species	**	*	*	*	ns	**
N Fertilization	ns	ns	ns	ns	ns	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	------------------- lignocellulose (%) -------------------					
Hard (Beacon)	30.8	30.0	29.8	29.4	30.8	31.3
Strong creeping red (Garnet)	26.0	28.2	27.0	26.5	29.6	26.7
Chewings (Rushmore)	27.8	29.2	28.5	27.6	30.4	29.1
LSD $_{(0.05)}$	1.0	1.3	1.5	2.7	ns	1.6
Annual N Fertilization						
0 kg ha^{-1}	27.9	29.6	28.7	27.8	30.5	29.4
49 kg ha^{-1}	28.4	29.0	28.7	27.7	30.1	29.1
98 kg ha^{-1}	27.9	28.9	28.3	28.3	30.7	28.7
146 kg ha^{-1}	28.7	29.0	28.1	27.5	29.6	29.0
LSD $_{(0.05)}$	ns	ns	ns	ns	ns	ns

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.13 Hemicellulose content of verdure as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
	ANOVA					
Source of variation						
Species	*	**	*	*	*	*
N Fertilization	ns	ns	ns	ns	ns	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	------------------- hemicellulose (%) -------------------					
Hard (Beacon)	37.5	37.2	39.3	36.2	35.6	36.5
Strong creeping red (Garnet)	32.7	34.9	35.9	33.2	33.3	33.8
Chewings (Rushmore)	36.7	35.7	37.4	35.0	35.2	35.4
LSD $_{(0.05)}$	2.5	0.9	1.0	2.7	1.2	1.7
Annual N Fertilization						
0 kg ha^{-1}	35.9	36.3	37.9	34.9	34.0	35.0
49 kg ha^{-1}	35.2	36.0	37.8	34.9	34.9	35.7
98 kg ha^{-1}	36.1	35.9	37.2	35.2	35.1	35.3
146 kg ha^{-1}	35.1	35.4	37.3	34.0	35.0	35.0
LSD $_{(0.05)}$	ns	ns	ns	ns	ns	ns

*Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
[§]ns, non-significant

Table 4.14 Lignin content of verdure as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
			ANOVA			
Source of variation						
Species	**	**	**	*	*	*
N Fertilization	ns	ns	ns	ns	ns	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	--------------------- lignin (%) ---------------------					
Hard (Beacon)	6.0	5.0	5.6	5.0	6.2	9.7
Strong creeping red (Garnet)	3.8	3.7	4.6	3.5	5.1	7.3
Chewings (Rushmore)	3.7	3.7	5.1	4.1	5.2	7.9
LSD $_{(0.05)}$	1.0	1.0	0.7	1.0	0.9	1.0
Annual N Fertilization						
0 kg ha^{-1}	4.5	4.2	4.9	4.0	5.8	8.3
49 kg ha^{-1}	4.5	3.9	4.9	4.2	5.1	8.1
98 kg ha^{-1}	3.9	4.0	5.0	4.2	5.9	8.1
146 kg ha^{-1}	5.2	4.3	5.6	4.4	5.4	8.7
LSD $_{(0.05)}$	ns	ns	ns	ns	ns	ns

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.15 Cellulose content of verdure as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
			ANOVA			
Source of variation						
Species	**	ns	*	ns	ns	*
N Fertilization	ns	ns	ns	ns	ns	ns
Species x N Fertilization	ns	ns	ns	ns	ns	ns
Species (Cultivar)	---------------------- cellulose (%) ----------------------					
Hard (Beacon)	24.8	25.0	24.2	24.4	24.6	21.6
Strong creeping red (Garnet)	22.2	24.5	22.4	23.0	24.5	19.4
Chewings (Rushmore)	24.1	25.5	23.4	23.5	25.2	21.2
LSD $_{(0.05)}$	1.2	ns	1.2	ns	ns	1.4
Annual N Fertilization						
0 kg ha^{-1}	23.4	25.4	23.8	23.8	24.7	21.1
49 kg ha^{-1}	23.8	25.1	23.7	23.5	25.0	20.9
98 kg ha^{-1}	24.0	24.9	23.3	24.1	24.8	20.6
146 kg ha^{-1}	23.5	24.7	22.5	23.1	24.1	20.4
LSD $_{(0.05)}$	ns	ns	ns	ns	ns	ns

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

Table 4.16 Carbon nitrogen ratio of verdure as affected by species and N fertilization during 2015 and 2016 on fine fescue turf seeded September 2012 on a loam in North Brunswick, NJ.

	2015			2016		
	May	June	Oct.	May	June	Nov.
	ANOVA					
Source of variation						
Species	***	***	**	***	***	***
N Fertilization	ns	***	***	***	***	***
Species x N Fertilization	ns	**	ns	ns	ns	ns
Species (Cultivar)	--------------------- C:N ratio ---------------------					
Hard (Beacon)	32.6	25.3	21.1	38.7	33.7	23.0
Strong creeping red (Garnet)	26.6	19.9	16.2	30.1	26.7	16.6
Chewings (Rushmore)	24.0	19.8	17.3	27.6	26.0	18.7
LSD $_{(0.05)}$	2.4	0.7	1.9	2.9	1.4	1.8
Annual N Fertilization						
0 kg ha^{-1}	28.0	24.6	21.5	34.3	33.1	20.6
49 kg ha^{-1}	28.0	22.5	18.5	32.5	29.8	20.0
98 kg ha^{-1}	27.7	20.3	17.1	31.8	27.6	19.0
146 kg ha^{-1}	27.3	19.3	15.5	29.9	24.6	18.1
LSD $_{(0.05)}$	ns	1.0	ns	ns	ns	ns

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
§ ns, non-significant

CHAPTER 5 Comparison of Cell Wall Composition in Five Fine Fescue Species during Different Harvest Time

ABSTRACT

Cell wall constituents have been reported to associate with wear tolerance of turfgrass. Research on forage grass indicated that harvest time and plant maturity have a significant effect on cell wall composition of grass; however, there is limited information on the effect of harvest time on the cell wall composition of fine fescues. The objective of this study was to compare the cell wall composition of five fine fescue species in different harvest time. Three field trials were seeded on a loam at Hort Farm 2 in North Brunswick, NJ in 2014, 2015, and 2016, respectively. Verdure samples were collected three times a year in May/June, August/September, and October/November to determine the concentration of cell wall constituents. Harvest time had a significant impact on the concentration of cell wall constituents of fine fescue species. However, the relative rankings of cell wall constituents among fine fescue species are relatively consistent despite the fluctuation in concentration caused by the harvest time. The concentrations of total cell wall (TCW), hemicellulose, lignocellulose and cellulose of six fine fescue species followed a similar trend: Sheep fescue Quatro > hard fescue Beacon and Blueray > Chewings fescue Radar = slender creeping red fescue Shoreline > strong creeping red fescue Marvel. The concentration of lignin was highly variable, and the ranking of fine fescue species was inconsistent. The results suggest that comparisons of cell wall composition among fine fescue species need to be conducted at a relatively similar time frame to avoid the introduction of variability due to different harvest time.

INTRODUCTION

Classically, cell wall constituents are grouped into cellulose, hemicelluloses, and lignin. Cellulose is the single most abundant component in plant cell walls, which is highly stable and insoluble in water. Hemicellulose is amorphous and soluble in alkaline or acid solutions, which comprise a diverse class of polysaccharides, including xylans, xyloglucans, glucomannans, and mixed-linkage glucan (Taiz and Zeiger, 1972). Hemicellulose assists the cellulose in forming cellulose-hemicellulose networks with greater inaccessibility (Aman, 1993). Lignin is a polymer composed of phenylpropanoid monolignol units, which are necessary to impart strength and rigidity to plant cell walls and provides mechanical support for aerial shoots and plant resistance to diseases, insects, cold temperatures, and other stresses (Rhodes, 1985).

Environmental factors have a significant impact on the growth, development, and quality of plants (Taiz and Zeiger, 1972). Forage grass grows at high temperatures generally have a higher concentration of cell wall components than at low temperatures as increasing temperatures often cause the conversion of soluble carbohydrates into structural polysaccharides (Buxton and Casler, 1993). Several studies confirmed that the concentration of total cell wall (TCW), hemicellulose, and cellulose increase with increasing temperature in forage grass (Moir et al., 1977; Henderson and Robinson, 1982; Fales, 1986). In turf research, Shearman and Beard (1975) found that TCW increased significantly from July to September but declined in October.

Drought stress often occurs with high temperature, which can also reduce cell wall concentration in grass. Halim et al. (l989a) reported that the concentration of cell wall constituents in both leaves and stems of alfalfa decreased with increasing severity of drought stress. Wilson (1976) attributed the influence of drought stress to slow growth rate and delay of further stem development, which results in leafier plants with low cell wall concentration.

Environmental factors, including climate, soil, and pest incident, may interact and alter plant cell wall composition. Results from the previous chapter suggested that harvest time had a significant impact on fine fescue cell wall composition. Thus, the objective of this study was to compare the cell wall composition of five fine fescue species during different harvest time.

MATERIALS AND METHODS

Site Description and Maintenance

Three trials were seeded on a Nixon loam (fine-loamy, mixed, mesic Typic Hapludults) at Hort Farm 2 in North Brunswick, NJ in 2014, 2015, and 2016, respectively. Soil test indicated that soil pH ranged from 5.9 to 6.4 from 2014 to 2018. Soil P ranged from 108 to 119 mg $kg^{-1,}$ and K ranged from 113 to 153 mg $kg^{-1}$from 2014 to 2018. All three trials were mowed at 6.4 cm once a week from April to November; mowing was suspended during drought and heat stress to avoid bruising damage. Irrigation was applied to avoid severe drought stress. Trial 1 received annual N rates of 50.3, 41.5, 64.2, 68.8, and 73.3 kg ha^{-1} from 2014 to 2018, respectively. Trial 2 received annual N rates of 51.3, 64.2, 68.8, and 73.3 kg ha^{-1} from 2015 to 2018, respectively. Trial 3 received annual N rates of 47.4, 68.8, and 73.3 kg ha^{-1} from 2016 to 2018, respectively. N was applied as ammonium sulfate and urea and K were applied as sulfate of potash with 16-0-8 granular N-P_2O_5-K_2O fertilizer.

Summer patch (caused by *Magnaporthiopsis poae*) and dollar spot (caused by *Clarireedia Jackson ii*) was suppressed by fluoxastrobin applied at a rate of 0.55 kg a.i. ha^{-1} on 19 May and 15 June in 2015, 19 May and 14 June 2015, 27 July 2017 in rotation with pyraclostrobin applied at 0.56 kg a.i. ha^{-1} on 6 July, 3 and 18 Aug., 17 Nov. in 2015, 23 May, 17 June, 14 July, 12 Aug., 2 Sep. and 31 Oct. 2016, 3 and 24 May, 16 Aug., 22 Sep. in 2017. Azoxystrobin and difenoconazole were also used to suppress summer patch and dollar spot at the rate of 0.32 and 0.20 kg a.i. ha^{-1}, respectively, on 14 May, 22 June and 6 July in 2017. Ipodione was also used to suppress dollar spot at the rate of 2.29 kg a.i. ha^{-1} on 5 September 2015 and 7 Sep. 2017. Pythium was controlled with cyazofamid applied at 2.75 kg a.i. ha^{-1} on 12 and 26 July 2016. Trifloxystrobin combined with triadimefon were applied to control pink snow mold (cause by *Michrodocium nivale*) at 0.61 kg a.i. ha^{-1} on 5 Dec. 2016 and 20 Nov. 2017. Leaf spot (caused by *Drechslera dictyoides*) was suppressed by penthiopyrad applied at 1.53 kg a.i. ha^{-1} on 12 May and 3 June 2016.

Sod webworm, chinch bugs, and white grubs were suppressed using bifenthrin applied at 0.25 kg a.i. $ha^{-1\ -1}$ on 21 Sept. and 2 Nov. in 2014; imidacloprid applied at 0.55 kg a.i. ha^{-1} and 0.61 kg a.i. ha^{-1} on 11 June 2015 and 17 May 2017; and clothianidin applied at 0.88 kg a.i. ha^{-1} on 4 Oct. 2016 and 1 June 2018.

Broadleaf weeds were controlled by 2,4-dichlorophenoxyacetic acid and rriclopyr applied at 0.8 and 0.27 kg a.i. ha^{-1}, respectively, on 13 May 2015; clopyralid and triclopyr applied at 0.29 and 0.13 kg a.i. ha^{-1}, respectively, on 19 April 2016; carfentrazone-ethyl applied at the rate of 0.03 kg a.i. ha^{-1}, 2,4-dichlorophenoxyacetic acid at the rate of 1.05 kg a.i. ha^{-1}, mecoprop applied at the rate of 0.33 kg a.i. ha^{-1}, and dicamba applied at the rate of 0.10 kg a.i. ha^{-1} on 27 April 2018. Dithiopyr was used to control crabgrass at a rate of 0.27 kg a.i preventatively. ha^{-1} on 1 May 2015, 12 April 2017, and 13 April 2018.

Experimental Design

Three independent randomized block design experiments with four replications were established on 11 September 2014 (Trial 1), 8 September 2015 (Trial 2), and 15 September 2016 (Trial 3) on a Nixon loam (fine-loamy, mixed, mesic Typic Hapludults) at Hort Farm 2 in North Brunswick, NJ. Two factors tested in this study were fine fescue species and harvest time. Each trial included five fine fescue species: strong creeping red fescue (*F. rubra* ssp. *rubra* 'Marvel'), slender creeping red fescue (*F. rubra* ssp. *littoralis* 'Shoreline'), Chewings fescue (*F. rubra* ssp. *commutata* 'Radar'), hard fescue (*F. brevipila* 'Beacon' and 'Blueray'), and sheep fescue (*F. ovina* 'Quatro').

Verdure samples were collected using a cutting shear (Gardena Canada LTD., Brampton, ON, Canada). The level of harvest time varied with trials. In Trial 1, verdure samples were collected at 8, 11, 14, 21, 31, 36 and 44 months after seeding (MAS) on 9 May, 18 August and 16 November 2015; 15 June 2016; 2 June and 1 September 2017; and 24 August 2018, respectively. Samples for Blueray hard fescue and Shoreline slender creeping red fescue were not collected at 36 and 44 MAS due to damage from summer patch (caused by *Magnaporthiopsis poae*). In Trial 2, verdure samples were collected at 9, 11, 14, 21, 24, and 32 MAS on 15 June, 22 August, and 28 November in 2016; 2 June and 1 September 2017; and 3 May 2018. In Trial 3, verdure samples were collected at 11, 20, and 23 MAS on 1 September 2017 and 3 May and 24 August 2018.

All verdure samples were oven-dried at 70 °C for 72 hours and ground using Wiley Mill (Thomas Scientific, Swedesboro, NJ) to pass a 1-mm sieve. Ground samples were subjected to fiber analysis based on the Goering and Van Soest (1970) methods described in Chapter 4.

Data Analysis

Data analyses were carried out individually for each trial due to the differences in the number of harvest dates. Statistical analyses were carried out using the Statistical Analysis System (SAS) software package (v. 9.4; SAS Institute), and data were subjected to analysis of variance (ANOVA) using the GLM procedure. Statistically significant main effects and interaction means were separated using Fisher's protected least significant difference test at the 0.05 probability level.

RESULTS

Both species and harvest time factors had a significant effect on the concentration of cell wall constituents, including total cell wall (TCW), lignocellulose, hemicellulose, lignin, and cellulose, in three trials (Table 5.1). The pooled concentrations of cell wall constituents across all harvest dates suggested that total cell wall, hemicellulose, lignocellulose, and cellulose of six fine fescue species followed a similar trend as sheep fescue > hard fescue > Chewings fescue = slender creeping red fescue > strong creeping red fescue (Table 5.1). The lignin concentration was the most variable cell wall constituent and did not have the same pattern as other cell wall constituents (Table 5.1).

Total Cell Wall

In Trail 1, the interaction of species and harvest time main effect was significant on TCW concentration (Table 5.1). Sheep fescue always had the greatest TCW concentration, while strong creeping red fescue had the lowest TCW concentration among all fine fescues (Table 5.2). The concentration of TCW was the lowest eight months after seeding (MAS) in May 2015 and was highest in August 2015 (11 MAS) and June 2017 (33 MAS) (Table 5.2).

In Trial 2 and Trial 3, the effect of species on TCW concentration was independent of harvest time (Table 1). Sheep fescue and hard fescue were among the species with the greatest TCW concentration across all harvest dates, while strong creeping red fescue was always the lowest in TCW concentration (Table 3 and Table 4). Samples harvested in August 2016 (11 MAS), June 2017 (21 MAS), September 2017 (24 MAS), and May 2018 (32 MAS) exhibited greater pooled TCW concentration across all species than samples harvested in June 2016 (9 MAS) and in November 2016 (14 MAS) (Table 5.3). The average TCW concentration pooled across all species collected in August 2018(23 MAS) from Trial 3 was greater than samples collected in September 2017 (11MAS) and in May 2018 (20 MAS).

Hemicellulose

The hemicellulose concentration of fine fescue species depended on harvest time in Trial 1 (Table 5.1). Similar to TCW concentration, sheep fescue and hard fescue were always among the group with the highest hemicellulose concentration, while strong creeping red exhibited the lowest hemicellulose concentration among all the fine fescues species in all harvest dates (Table 5.5). The hemicellulose concentration of samples harvested in August 2016 (11 MAS) was greater than any other harvest dates; however, the difference among fine fescue species was less apparent on this harvest date (Table 5.5).

In Trial 2 and Trial 3, the effect of species on hemicellulose concentration was independent of harvest time (Table 5.1). Hard fescue had greater average hemicellulose concentration than strong creeping red fescue; the hemicellulose concentrations of other species were intermediate and not statistically different (Table 5.6 and Table 5.7). Hemicellulose concentration tends to be higher as fine fescue matures. In Trial 2, samples harvested in September 2017 (24 MAS) had greater hemicellulose concentration than samples harvested in June (9 MAS), August (11 MAS), and November (14 MAS) in 2016 (Table 5.6). In Trial 3, hemicellulose concentration for samples harvested in August 2018 (23 MAS) was greater than samples harvested in September 2017 (11 MAS) and May 2018 (20 MAS) (Table 7).

Lignocellulose

The lignocellulose concentration of fine fescue species depended on harvest time in Trial 1 and Trial 2 (Table 5.1). Sheep fescue had the greatest lignocellulose concentration, while strong creeping red fescue exhibited the lowest lignocellulose concentration when the differences among fine fescue species were significant (Table 5.8 and Table 5.9). Greatest lignocellulose concentration was observed in spring (33 MAS) in Trial 1 and summer (11 MAS and 24 MAS) in Trial 2 (Table 5.8 and Table 5.9).

The species main effect on lignocellulose concentration was independent of harvest time in Trial 3 (Table 5.1). Pooled lignocellulose concentration across all harvest dates of sheep fescue and hard fescue were greater than slender creeping red fescue and strong creeping red fescue (Table 5.10). Greater hemicellulose concentration was observed in August 2018 (MAS) than in September 2017 (11 MAS) and May 2018 (20 MAS).

Cellulose

The cellulose concentration of fine fescue species depended on harvest time in Trial 1; the difference of cellulose concentration among species was significant on four of seven harvest dates (Table 5.1). Sheep fescue and Chewings fescue were among the groups with the highest cellulose concentration, while strong creeping red fescue and slender creeping red fescue exhibited the lowest cellulose concentration when differences among fine fescues were significant (Table 5.11).

In Trial 2 and Trial 3, harvest time did not interact with species main effect on cellulose concentration (Table 5.1). Pooled cellulose concentration of sheep fescue and Chewings fescue were greater than strong creeping red fescue (Table 5.12 and 5.13). In Trial 2, cellulose concentrations of samples harvested in May 2016 (14 MAS) and September 2017 (24 MAS) were lower than other harvest dates (Table 5.12). In Trial 3, cellulose concentration of samples harvested in September 2017 (11 MAS) was the greatest among all harvest dates (Table 5.13).

Lignin

The lignin concentration of fine fescues depended on harvest time was significant in Trial 1 and Trial 2 (Table 5.1). The difference of lignin concentration among species was significant on two of seven harvest dates in Trial 1. Strong creeping red fescue had higher lignin concentration than sheep fescue in June 2017 (33 WAS); however, Quatro sheep fescue exhibited the highest lignin concentration in August 2018 (44 WAS) (Table 5.14). In Trial 2, the difference among species was significant on four of six harvest dates, while no clear pattern was observed (Table 5.15).

The lignin concentration of fine fescues in Trial 3 was independent of harvest (Table 5.1). Chewings fescue and hard fescue exhibited the greatest lignin concentration among all the species (Table 5.16). Pooled lignin concentration across all fine fescue species indicated an increase of the average lignin concentration as fine fescues become more mature (Table 5.16).

DISCUSSION

Buxton and Casler (1993) noted the increasing temperatures often cause the conversion of soluble carbohydrates into structural polysaccharides, which resulted in a greater cell wall concentration. Shearman and Beard (1975) studied the effect of harvest time on seven cool-season grass species and reported the ranking for TCW concentration from high to low: Chewings fescue > strong creeping red fescue > perennial ryegrass > Kentucky bluegrass > Italian ryegrass > rough bluegrass. They also reported that TCW concentration increased significantly from July to September but declined in October. In this study, harvest time also had a significant impact on the concentration of cell wall constituents in fine fescue species; the pooled TCW content was greater in August compared to May/June and November in Trial 1 and Trial 2 during the first year of assessment. However, due to the summer patch outbreak, there were not enough sampling dates in the second and third year to confirm the temporal pattern.

Shearman and Beard (1975) also monitored the changes of cell wall constituents in the growth chamber during the first ten-week after seedling emergence. They noted a trend of increasing percent TCW with seedling maturity among the species tested with the exception Italian ryegrass (*Lolium multiflorurn*) and Kentucky bluegrass. There was no evidence in our study to show the maturity effect on fine fescue cell wall composition. However, it is important to note that Shearman and Beard (1975) conducted their study in growth chambers with a controlled environment and the samples were collected at a very immature stage of the grasses (within the first ten weeks of seedling emergence). The TCW reported in their study for Chewings fescue and strong creeping red fescue were 48.5%, and 49.8%, respectably on week four and 52.6%, and 51.0 % on week ten, which were much lower than the TCW range (>60%) found in our study.

The other explanation for not seeing the change of cell wall composition could be the management practices. Wilson (1976) suggested that the increased concentration of cell wall constituents with maturation primarily resulted from a decrease in the leaf-to-stem ratio in forage grass. Stems contain a higher proportion of thick-walled tissues (sclerenchyma, xylem fiber, and xylem vessel) and less photosynthetic tissues (mesophyll, chlorenchyma) than leaves, resulting in stems having a higher cell wall concentration than leaves. In their growth champer study, Shearman and Beard (1975) reported a greater concentration of TCW, lignocellulose, hemicellulose, cellulose, and lignin in the leaf sheath than leaf blades. It is possible that the development of leaf sheaths during the early growing stage contributed to the increase of cell wall content. In addition, Shearman and Beard (1975) collected samples from un-mowed seedling which increase the chance to include more leaf sheaths with higher cell wall concentration than leaf blades. Under conditions of more mature plants that are routinely mowed, the ratio between leaf blades and leaf sheaths would likely remain relatively similar. The effect of mowing-induced changes in leaf morphology and asoociated cell wall composition of fine fescues has not been experimentally tested.

CONCLUSION

The relative ranking of cell wall concentration among these fine fescue species tested is relatively consistent after establishment despite the fluctuation in concentration associated with harvest time. The rankings of six fine fescue species for concentrations of TCW, hemicellulose, lignocellulose and cellulose were relatively similar. In general, the *F. ovina* complex (Sheep fescue and hard fescue) had higher concentrations of TCW, lignocellulose, hemicellulose, and cellulose than the *F. rubra* complex (Chewings fescue, strong creeping red fescue, and slender creeping red fescue). The concentration of lignin was highly variable, and the ranking of fine fescue species was inconsistent.

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Table 5.1 Analysis of variance of concentration of cell wall constituents as affected by species and harvest time in three trials seeded to fine fescues on a SOIL in North Brunswick, NJ.

	---Total cell wall---			---Hemicellulose---			---Lignocellulose---			----Cellulose----			-----Lignin-----		
	Trial 1[ǂ]	Trial 2[ꜜ]	Trial 3[£]	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
Source of variation															
Species (S)	***	***	***	***	***	*	***	***	*	***	***	*	*	***	*
Harvest Time (HT)	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
S x HT	***	ns	ns	*	ns	ns	*	*	ns	***	ns	ns	*	*	ns
Species	Total cell wall (%)			Hemicellulose (%)			Lignocellulose (%)			Cellulose (%)			Lignin (%)		
Quatro[SHf]	67.7	64.7	66.8	36.0	33.9	32.7	31.8	30.9	34.1	25.0	22.5	21.8	6.8	8.4	12.3
Beacon[HD]	66.3	64.7	68.2	35.8	33.5	33.3	30.5	31.2	34.9	23.8	22.1	22.1	6.8	9.1	12.8
Blueray[HD]	65.1	64.9	67.1	35.3	34.2	34.8	29.8	30.7	32.3	23.5	22.2	22.4	6.4	8.5	9.9
Radar[CH]	63.8	62.0	65.3	34.1	33.2	32.9	29.7	28.9	32.4	24.1	22.5	23.0	5.6	6.6	9.4
Shoreline[SL]	63.2	62.9	63.6	34.4	32.2	32.7	28.8	30.7	30.9	23.0	21.5	21.1	5.8	9.2	9.8
Marvel [ST]	60.7	60.1	60.9	32.1	31.7	30.2	28.6	28.4	30.7	22.5	21.0	20.4	6.2	7.5	10.3
LSD (0.05)	2.0	2.5	2.0	1.5	2.2	2.8	1.8	2.5	2.9	1.7	2.5	2.7	1.0	2.6	2.2

*Significant at $p \leq 0.05$** Significant at $p \leq 0.01$

*** Significant at $p \leq 0.001$

[§]ns, non-significant

[ǂ]Trial 1 was seeded 11 September 2014 and sampled at 8, 11, 14, 21, 33, 36, and 44 months after seeding

[ꜜ]Trial 2 was seeded 8 September 2015 and sampled at 9, 11, 14, 21, 24, and 32 months after seeding

[£]Trial 3 was seeded 15 September 2016 and sampled at 11, 20, and 23 months after seeding

[f]Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 5.2 Total cell wall content as affected by the interaction of species and harvest time during the 44 weeks after a September 2014 seeding of fine fescues (Trail 1) on a loam in North Brunswick NJ.

	Harvest Time (months after seeding)						
	May 2015 (8)[§]	Aug. 2015 (11)	Nov. 2015 (14)	June 2016 (21)	June 2017 (33)	Sept. 2017 (36)	Aug. 2018 (44)
	---------------------------------- total cell wall (%) ----------------------------------						
Species							
Quatro[SHf]	66.3	69.6	66.5	67.4	70.7	66.3	67.3
Beacon[HD]	61.6	66.6	67.6	64.7	69.2	68.4	66.3
Blueray[HD]	62.1	66.8	65.4	66.0	NA[€]	NA	NA
Radar[CH]	61.9	64.9	65.1	61.3	66.1	65.7	61.6
Shoreline[SL]	62.0	64.9	62.5	63.9	NA	NA	62.9
Marvel [ST]	54.8	63.5	60.6	59.4	63.6	63.4	59.6
LSD (0.05)				2.4			

[§] Month after seeding

[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

[€]Sample not collected due to summer patch disease

Table 5.3 Total cell wall concentration as affected by the main effects of species and harvest time during the 32 months after a September 2015 seeding of fine fescues (Trail 2) on a loam in North Brunswick NJ.

	Total cell wall (%)
Species	
Quatro[SHf]	64.7
Beacon[HD]	64.7
Blueray[HD]	64.9
Radar[CH]	62.0
Shoreline[SL]	62.9
Marvel [ST]	60.1
LSD (0.05)	2.5
Harvest Time (months after seeding)	
June 2016 (9) [§]	59.9
Aug. 2016 (11)	65.0
Nov. 2016 (14)	57.2
June 2017 (21)	64.9
Sept. 2017 (24)	67.5
May 2018 (32)	64.9
LSD (0.05)	2.5

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 5.4 Total cell wall concentration as affected by the main effects of species and harvest time during the 23 months after a September 2016 seeding of fine fescues (Trail 3) on a loam in North Brunswick, NJ.

	Total cell wall (%)
Species	
Quatro[SHf]	66.8
Beacon[HD]	68.2
Blueray[HD]	67.1
Radar[CH]	65.3
Shoreline[SL]	63.6
Marvel [ST]	60.9
LSD (0.05)	2.0
Harvest Time (months after seeding)	
Sept. 2017 (11)[§]	62.1
May 2018 (20)	62.6
Aug. 2018 (23)	69.1
LSD	2.9

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 5.5 Hemicellulose concentration as affected by the interaction of species and harvest time during the 44 weeks after a September 2014 seeding of fine fescues (Trial 1) on a loam in North Brunswick NJ.

	Harvest Time (months after seeding)						
	May 2015 (8)[§]	Aug. 2015 (11)	Nov. 2015 (14)	June 2016 (21)	June 2017 (33)	Sept. 2017 (36)	Aug. 2018 (44)
	---------- hemicellulose (%) ----------						
Species							
Quatro[SHf]	35.9	38.4	36.0	35.9	35.9	35.6	34.3
Beacon[HD]	34.9	37.4	36.9	34.3	33.9	37.8	35.5
Blueray[HD]	34.6	37.4	34.1	35.0	NA[€]	NA	NA
Radar[CH]	34.9	36.4	35.5	32.9	30.9	36.3	31.6
Shoreline[SL]	35.3	36.4	33.8	33.5	NA	NA	33.2
Marvel [ST]	30.4	35.2	32.6	31.6	28.6	34.7	31.4
LSD (0.05)				2.2			

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red
[€] Sample not collected due to summer patch disease

Table 5.6 Hemicellulose concentration as affected by the main effects of species and harvest time during the 32 weeks after a September 2015 seeding of fine fescues (Trial 2) on a loam in North Brunswick NJ.

	Hemicellulose (%)
Species	
Quatro[SHf]	33.9
Beacon[HD]	33.5
Blueray[HD]	34.2
Radar[CH]	33.2
Shoreline[SL]	32.2
Marvel [ST]	31.7
LSD (0.05)	2.0
Harvest Time (months after seeding)	
June 2016 (9) [§]	32.4
Aug. 2016 (11)	32.7
Nov. 2016 (14)	30.0
June 2017 (21)	34.1
Sept. 2017 (24)	35.5
May 2018 (32)	34.0
LSD (0.05)	2.0

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 5.7 Hemicellulose concentration as affected by the main effects of species and harvest time during the 23 weeks after a September 2016 seeding of fine fescues (Trial 3) on a SOIL in North Brunswick NJ.

	Hemicellulose (%)
Species	
Quatro[SHf]	32.7
Beacon[HD]	33.3
Blueray[HD]	34.8
Radar[CH]	32.9
Shoreline[SL]	32.7
Marvel [ST]	30.2
LSD (0.05)	2.9
Harvest Time (months after seeding)	
Sept. 2017 (11)[§]	32.0
May 2018 (20)	30.9
Aug. 2018 (23)	34.4
LSD (0.05)	2.1

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 5.8 Lignocellulose concentration as affected by the interaction of species and harvest time during the 44 weeks after an September 2014 seeding (Trial 1) on a loam in North Brunswick NJ.

	Harvest Time (months after seeding)						
	May 2015 (8)[§]	Aug. 2015 (11)	Nov. 2015 (14)	June 2016 (21)	June 2017 (33)	Sept. 2017 (36)	Aug. 2018 (44)
	------------------ lignocellulose (%) ------------------						
Species							
Quatro[SHf]	30.5	31.2	30.5	31.5	34.8	30.7	33.1
Beacon[HD]	26.7	29.2	30.7	30.5	35.3	30.6	30.8
Blueray[HD]	27.6	29.3	31.3	31.0	NA[€]	NA	NA
Radar[CH]	27.0	28.5	29.6	28.4	35.1	29.4	30.0
Shoreline[SL]	26.7	28.5	28.8	30.4	NA	NA	29.7
Marvel [ST]	24.4	28.3	28.1	27.9	35.0	28.6	28.2
LSD (0.05)				1.8			

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red
[€] Sample not collected due to summer patch disease

Table 5.9 Lignocellulose concentration as affected by the interaction of species and harvest time during the 32 weeks after an September 2015 seeding of fine fescues (Trial 2) on a loam in North Brunswick NJ.

	Harvest Time (months after seeding)					
	June 2016 (9) §	Aug. 2016 (11)	Nov. 2016 (14)	June 2017 (21)	Sept. 2017 (24)	May 2018 (32)
	-- lignocellulose (%)--					
Species						
Quatro[SHf]	28.8	33.0	27.0	31.9	32.8	31.6
Beacon[HD]	27.9	33.2	30.3	30.8	32.6	32.6
Blueray[HD]	28.6	33.7	25.6	30.9	33.1	32.5
Radar[CH]	25.9	30.8	25.7	30.9	29.7	30.5
Shoreline[SL]	28.2	33.4	28.7	30.8	34.6	28.4
Marvel [ST]	25.7	29.4	26.2	30.1	29.3	29.9
LSD (0.05)			2.0			

§ Month after seeding

f Species designated by SH = sheep; HD = hard; CH = Chewings; ST = strong creeping red; SL = slender creeping red

Table 5.10 Lignocellulose concentration as affected by the main effects of species and harvest time during the 23 months after a September 2016 seeding of fine fescues (Trial 3) on a loam in North Brunswick, NJ.

	Lignocellulose (%)
Species	
Quatro[SHf]	34.1
Beacon[HD]	34.9
Blueray[HD]	32.3
Radar[CH]	32.4
Shoreline[SL]	30.9
Marvel [ST]	30.7
LSD (0.05)	2.8
Harvest Time (months after seeding)	
Sept. 2017 (11)[§]	30.2
May 2018 (20)	31.7
Aug. 2018 (23)	34.7
LSD (0.05)	4.0

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 5.11 Cellulose concentration as affected by the interaction of species and harvest time during the 44 weeks after a September 2014 seeding of fine fescues (Trial 1) on a loam in North Brunswick NJ.

	Harvest Time (months after seeding)						
	May 2015 (8)[§]	Aug. 2015 (11)	Nov. 2015 (14)	June 2016 (21)	June 2017 (33)	Sept. 2017 (36)	Aug. 2018 (44)
	---------- cellulose (%) ----------						
Species							
Quatro[SHf]	26.2	25.4	23.4	25.8	26.6	23.8	23.5
Beacon[HD]	23.0	24.0	23.1	24.3	24.8	23.7	23.9
Blueray[HD]	23.7	23.5	22.6	24.0	NA[€]	NA	NA
Radar[CH]	24.2	23.9	22.3	23.7	25.8	24.0	24.9
Shoreline[SL]	22.6	22.8	22.0	23.4	NA	NA	24.1
Marvel [ST]	20.9	23.2	21.3	22.5	23.1	23.2	23.0
LSD (0.05)				2.1			

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red
[€]Sample not collected due to summer patch disease

Table 5.12 Cellulose concentration as affected by the main effects of species and harvest time during the 32 weeks after a September 2015 seeding of fine fescues (Trial 2) on a loam in North Brunswick NJ.

	Cellulose (%)
Species	
Quatro^{SHf}	22.5
Beacon^{HD}	22.1
Blueray^{HD}	22.2
Radar^{CH}	22.5
Shoreline^{SL}	21.5
Marvel ST	21.0
LSD (0.05)	1.4
Harvest Time (months after seeding)	
June 2016 (9) [§]	22.9
Aug. 2016 (11)	22.0
Nov. 2016 (14)	20.0
June 2017 (21)	22.8
Sept. 2017 (24)	20.2
May 2018 (32)	23.7
LSD (0.05)	1.4

[§] Month after seeding

[f] Species designated by ^{SH} = sheep; ^{HD} = hard; ^{CH} = Chewings; ST = strong creeping red; ^{SL} = slender creeping red

Table 5.13 Cellulose concentration as affected by the main effects of species and harvest time during the 23 weeks after a September 2016 seeding of fine fescues (Trial 3) on a SOIL in North Brunswick NJ.

	Cellulose (%)
Species	
Quatro[SHf]	21.8
Beacon[HD]	22.1
Blueray[HD]	22.4
Radar[CH]	23.0
Shoreline[SL]	21.1
Marvel [ST]	20.4
LSD (0.05)	2.2
Harvest Time (months after seeding)	
Sept. 2017 (11)[§]	22.9
May 2018 (20)	21.6
Aug. 2018 (23)	20.9
LSD (0.05)	1.1

[§] Month after seeding

[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

Table 5.14 Lignin concentration as affected by the interaction of species and harvest time during the 44 weeks after a September 2014 seeding of fine fescues (Trial 1) on a loam in North Brunswick NJ.

	Harvest Time (months after seeding)						
	May 2015 (8)[§]	Aug. 2015 (11)	Nov. 2015 (14)	June 2016 (21)	June 2017 (33)	Sept. 2017 (36)	Aug. 2018 (44)
	--- lignin (%) ---						
Species							
Quatro[SHf]	4.3	5.9	7.1	5.7	8.2	6.9	9.6
Beacon[HD]	3.8	5.3	7.6	6.2	10.5	7.0	6.9
Blueray[HD]	4.0	5.9	8.7	7.0	NA[€]	NA	NA
Radar[CH]	2.8	4.6	7.4	4.8	9.3	5.3	5.1
Shoreline[SL]	4.0	5.7	6.8	7.0	NA	NA	5.5
Marvel [ST]	3.5	5.1	6.8	5.4	12.0	5.4	5.2
LSD (0.05)				2.9			

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red
[€]Sample not collected due to summer patch disease

Table 5.15 Lignin concentration as affected by the main effects of species and harvest time during the 32 weeks after a September 2015 seeding of fine fescues (Trial 2) on a loam in North Brunswick NJ.

	Harvest Time (months after seeding)					
	June 2016 (9) §	Aug. 2016 (11)	Nov. 2016 (14)	June 2017 (21)	Sept. 2017 (24)	May 2018 (32)
	------ lignin (%) ------					
Species						
Quatro[SHf]	4.5	10.1	6.8	7.3	13.0	8.5
Beacon[HD]	5.3	10.7	10.4	7.7	12.4	7.9
Blueray[HD]	5.4	11.4	5.7	7.9	12.2	8.5
Radar[CH]	3.3	9.5	5.3	7.8	7.7	5.7
Shoreline[SL]	5.5	11.8	8.2	8.7	16.0	4.8
Marvel [ST]	3.9	7.9	7.4	8.6	9.3	7.8
LSD (0.05)			3.1			

§ Month after seeding

f Species designated by SH = sheep; HD = hard; CH = Chewings; ST = strong creeping red; SL = slender creeping red

Table 5.16 Lignin concentration as affected by the main effects of species and harvest time during the 23 weeks after a September 2016 seeding of fine fescues (Trial 3) on a SOIL in North Brunswick NJ.

	Lignin (%)
Species	
Quatro[SHf]	12.3
Beacon[HD]	12.8
Blueray[HD]	9.9
Radar[CH]	9.4
Shoreline[SL]	9.8
Marvel [ST]	10.3
LSD (0.05)	3.2
Harvest Time (months after seeding)	
Sept. 2017 (11)[§]	7.3
May 2018 (20)	10.1
Aug. 2018 (23)	13.8
LSD (0.05)	5.7

[§] Month after seeding
[f] Species designated by [SH] = sheep; [HD] = hard; [CH] = Chewings; [ST] = strong creeping red; [SL] = slender creeping red

CHAPTER 6 Near-Infrared Reflectance Spectroscopy to Predict Concentration of Nitrogen and Cell Wall Constituents in Three Fine Fescue Species

ABSTRACT

Near-infrared reflectance spectroscopy (NIRS) provides a fast and accurate way to predict various constituents in agricultural products. The objective of this study was to i) develop NIRS calibration models to predict the concentration of total nitrogen (N), total carbon (C), and cell wall constituents in fine fescues and ii) to ascertain whether a universal calibration could accommodate multiple fine fescue species. Samples for analysis were collected over four years from different locations for maximum variability. In general, NIRS models to provide very accurate prediction (R^2_{cal} > 0.93) for total N at the species-specific level and across different species. The prediction accuracy was less favorable for cell wall constituents due to the complexity of plant cell walls. For species-specific models, the predicting accuracy for total cell wall (TCW; R^2_{cal} > 0.70), lignocellulose (R^2_{cal} > 0.78) and hemicellulose (R^2_{cal} > 0.79) were moderately successful. A universal model across all species was less precise than species-specific models, but still acceptable for predicting TCW (R^2_{cal} =0.77), lignocellulose (R^2_{cal} =0.86) and hemicellulose (R^2_{cal} =0.75).

INTRODUCTION

Determination of cell wall composition using the conventional analytical method can be expensive and time-consuming. Near-infrared reflectance spectroscopy (NIRS) provides a non-destructive, fast, and accurate way to estimate constituents of interest in agricultural products (Norris et al., 1976). The NIRS method acquires qualitative and/or quantitative information from a sample based on the vibration of molecular bonds in the near-infrared electromagnetic region (700- to 2500-nm). Molecular vibrations can occur in the form of X-H, where X can be carbon (C), nitrogen (N), oxygen (O) or sulfur (S), due to hydrogenic stretching (a change in the length of a bond), bending (a change in the angle between two bonds), or deformation vibration.

The application of NIRS is based on a calibration model which develops a mathematical relationship between the spectral data and the constituent of interest. Calibration of NIRS is based on Beer's Law, the absorbance of a homogeneous sample containing an absorbing substance is linearly proportional to the concentration of the absorbing species (Shenk et al., 1992). Partial least squares (PLS) regression is the most widely used regression method, which summarizes useful information from all wavelengths into several PLS factors (Workman, 2008). It continues to be the most commonly used multivariate analysis technique due to its faster convergence to the optimum prediction performance (Wentzell and Montoto, 2003).

Protein and structural carbohydrates are common constituents in agricultural products determined by NIRS (García-Sánchez et al., 2017). The objective of this study was to i) develop NIRS calibration models to predict cell wall composition and total nitrogen (N) and carbon (C) content of fine fescues and ii) to ascertain whether a universal calibration could accommodate multiple fine fescue species.

MATERIALS AND METHODS

Sample Collection and Near-infrared Reflectance Analysis

A total of 230 Chewings fescue samples, 229 hard fescue samples, and 214 strong creeping fescue samples were collected from research farms in Freehold and North Brunswick, NJ, and St. Paul, MN during 2017 and 2018 and used to develop NIRS models to predict cell wall constituent values (Appendix A; Table A.1 to A.3). Total of 211 samples (71 Chewings fescues, 68 hard fescues, and 72 strong creeping red fescues) were collected from a nitrogen (N) fertilization rate study in North Brunswick, NJ to predict tissue total N, total carbon (C) and C:N ratio (Appendix A; Table A.3 to A.6).

Verdure samples were collected using Gardena grass shear (GARDENA CANADA LTD., Brampton, ON, Canada). Samples were dried in an oven at 70 °C for 72 hours and ground using Wiley Mill (Thomas Scientific, Swedesboro, NJ) to pass a 1-mm sieve. Spectra of ground samples were collected using an industrial NIR monochromator scanning spectrometer Spectra Star 2400 (Unity Scientific, Milford, MA, USA). Samples were placed in a 35-mm diameter stationary cup (Unity Scientific, Milford, MA, USA) and loaded into the Spectra Star 2400 and scanned to obtain a spectrum between 1200 and 2400 nm at 1 nm intervals.

Reference Analysis

Fiber analysis was performed using the methods described by Goering and Van Soest (1970). The neutral detergent fiber (NDF) procedure determined TCW concentration on a dry weight basis; acid detergent fiber (ADF) determined lignocellulose concentration; the difference between the quantity of NDF and ADF value estimated the hemicellulose concentration. Acid detergent lignin (ADL) determined the lignin concentration and the difference between the quantity of ADF and ADL estimated cellulose concentration. Total N content, total C content, and C:N ratio was measured on approximately 1-gram of the sample by the Dumas combustion method (Kirsten, 1983).using a Vario MAX cube analyzer (Elementar, Hanau, Germany).

Descriptive statistics of cell wall constituents and total N and total C were carried out using the Statistical Analysis System (SAS) software package (v. 9.4; SAS Institute), and data were subjected to analysis of variance (ANOVA) using the GLM procedure. Means were separated using Fisher’s protected least significant difference test at the 0.05 probability level.

Calibration and Validation

Calibration models were developed using UCal NIR calibration software (version 3.0, Unity Scientific, Milford, MA, USA). Derivative spectra were used to emphasize small or large absorption peaks and minimize overlapping peaks and baseline correction. The standard normal variate (SNV) scatter correction was applied, along with the detrend function for developing accurate, stable calibrations (Shenk and Westerhaus, 1994). Principal component analysis (PCA) was used to detect possible spectral outliers before model calibration. A maximum standardized Mahalanobis distance (global distance) of 3.0 was used to establish population boundaries to detect spectral outliers.

Calibration models were developed using partial least squares (PLS) regression. Both species-specific calibration models and a universal (across three species) calibration model were developed to predict constituent contents of verdure samples. Calibration models were also established for the population of fine fescues in which just one species was omitted from the model. The calibration model obtained was then used to predict chemical parameters of the omitted sample species to determine to what extent the NIRS model can accommodate unknown species not represented in the calibration model.

During the development of calibration models, a cross-validation technique was used to evaluate the robustness of the calibration models. The data were split into ten subsets, and calibrations were performed leaving one subset out of the model. And the model was then used to predict the parameters for the excluded samples. The prediction errors for each subset were pooled to the standard error of cross-validation (SECV). The optimal number of factors to be included in the PLS model was determined by full cross-validation with the lowest SECV (Shenk and Westerhaus, 1994).

The prediction accuracy of the models was assessed by statistics including coefficient of determination in calibration (R^2_{cal}) and standard error of calibration (SEC) defined as the variability in the difference between reference and predicted values. The coefficient of determination in calibration (R^2_{cv}) and SECV provides a more realistic estimate of the prediction error when the calibration is applied to an unknown set of samples. The ratio of the population standard deviation (SD) and the SECV defined the residual predictive deviation (RPD = SD/SECV) for the NIR predictions to evaluate how well a calibration model predicted chemical data (Williams, 2000).

RESULTS AND DISCUSSION

Cell Wall Composition Prediction Models

The mean values, standard deviation, and range of cell wall constituents of Chewings fescue (n=230), hard fescue (n=229), and strong creeping red fescue(n=214) are summarized in Table 6.1. The analysis of variance (ANOVA) indicated a significant difference in TCW, hemicellulose, lignin, and cellulose among fine fescue species. The ranking of these constituents from high to low were: Chewings fescues > hard fescue > strong creeping red fescue (Table 6.1). All three species exhibited a wide range in both cell wall composition, and the variability was considered suitable for developing NIRS calibration models.

Values for R^2_{cal} greater than 0.67 indicate a high predictive accuracy, a range of 0.33 - 0.67 indicated a moderated accuracy, R^2_{cal} between 0.19 and 0.33 indicate low accuracy, while the R^2_{cal} value below 0.19 considered unacceptable (Chin, 1998; Henseler et al., 2009). Table 6.2 summarize the statistics for species-specific models and the universal model. High coefficients of determination in calibration (R^2_{cal}) were observed in the models for predicting TCW (0.70 to 0.79; Figure 6.1), lignocellulose (0.78 to 0.91; Figure 6.2) and hemicellulose (0.78 to 0.82; Figure 6.3). The equations to predict lignin (Table 6.2; Figure 6.4) had moderate accuracy with R_{cal}^2 ranging from 0.62 to 0.76. The equation to predict cellulose in hard fescue had high accuracy with R_{cal}^2= 0.81, but low accuracy was obtained for equations to predict cellulose in Chewings fescue (0.35) and strong creeping red fescue (0.39) (Table 6.2; Figure 6.5). The calibrations statistics for cell wall constituents in fine fescue species were not as successful as reported by Norris et al. (1976) to predict TCW (R_{pre}^2 =0.98), lignocellulose

(R_{cal}^2 =0.98), and lignin (R_{cal}^2 =0.96) for forage grass and by Nousiainen et al. (2003) for predicting TCW (R_{cal}^2 = 0.96) of silage grass. The potential factors that can affect the correlation between NIRS spectrum and cell wall constituents include variable absorbance due to C–H bonds in indigestible cell wall carbohydrates and overlap with the absorbance of digestible components of TCW and soluble carbohydrate like sugar and starch (Wilman et al., 2000).

The universal model combining all species had similar calibration statistics as the individual species-specific models (Table 6.2), which indicate that a universal NIRS calibration model was able to accommodate multiple fine fescue species. Bruno-Soares et al. (1998) developed NIRS models for TCW (R_{cal}^2=0.97), hemicellulose (R_{cal}^2=0.96), and lignin (R_{cal}^2=0.87) across different species of green crop cereals including oats, barley, wheat, ryegrass, and sorghum. However, the author suggested a thorough validation before employing a model in practice due to the complexity of combining various species into a single NIRS calibration model.

Cross-validation was evaluated by the coefficient of determination in calibration (R^2_{cv}) and standard error of cross-validation (SECV). These two statistics provide a more realistic estimate of the prediction error when the calibration is applied to an unknown set of samples. The residual predictive deviation (RPD = SD/SECV) is often applied to evaluate how well a calibration model can predict chemical data; a greater value of the RPD indicates a greater probability of the model to accurately predict the chemical composition of unknown samples (Williams, 2000). Malley et al. (2003) proposed a guideline for evaluating calibrations for environmental samples based on the R^2_{cal} and the RPD. Excellent calibrations are with R^2_{cal} > 0.95 and RPD > 4; successful calibrations are with R^2_{cal} = 0.9–0.95 and RPD = 3–4; moderately successful calibrations are with R^2_{cal} = 0.8–0.9 and RPD = 2.25–3; moderately useful ones have R^2_{cal} = 0.7–0.8 and RPD = 1.75–2.25. In this study, R^2_{cv} values for TCW, lignocellulose, and hemicellulose were greater than 0.69 in all three species-specific models and the universal model (Table 4). Based on this guideline, moderately successful calibrations were established to predict TCW, hemicellulose, and lignocellulose in both species-specific models and the universal model.

Three calibration models were developed to predict cell wall constituents of the omitted species. The prediction of lignocellulose and hemicellulose was most successful (R^2_{pre}>0.70) regardless of the omission of one species (Table 6.3). The prediction accuracy for the cellulose content of Chewings and strong creeping red fescue was not successful (R^2_{pre}<0.30) when either of the species was excluded from the model. The prediction accuracy of TCW (R^2_{pre} = 0.48 to 0.65) and lignin (R^2_{pre} = 0.57 to 0.64) also decreased as the results of omitting the species (Table 6.3)

Total N and Total C Models

A different set of samples (n=211) was used to develop calibration models for predicting total C, total N, and C:N ratio. Total C, total N, and C:N ratio of Chewings fescue (n=71), hard fescue (68), and strong creeping red fescue (72) are summarized in Table 6.4. Hard fescues had the greatest total C and C:N ratio and the lowest total N among four fine fescue species. All three species exhibited a wide range of total N and total C content, and the variability was considered suitable for developing NIRS calibration models.

Both the calibration and cross-validation indicated very precise and accurate predictions for total N (Figure 6.6) and C:N ratio in both the species-specific models and the universal model; all the R^2_{cal} values greater than 0.96 and all the RPD values greater than 4.0 (Table 6.5). The R^2_{cal} values for equations to predict total C (Figure 6.7) were slightly lower in Chewings fescue (0.85), strong creeping red fescue (0.79), and in the universal model (0.75). Poor correlation was observed for the equation to predict total C in hard fescues (R^2_{cal} =0.39), which also had the smallest range in total C as measured by the reference method (Table 6.5). The accuracy of NIR equations to predict total N in fine fescues was similar to studies predicting total N in maize (n=398; R^2_{cal} =0.96 for leaves samples and R^2_{cal} =0.99 for stems; Volkers et al., 2003) and total N in grass silage (n=144; R^2_{cal} =0.94; Hermida et al., 2005).

The prediction precision and accuracy of total N and C:N ratio was unaffected by the omission of Chewings fescue, strong creeping red fescue, and slender creeping red fescue (Table 6.6). The omission of hard fescue in the model slightly reduced the precision of the equation but still provide very reliable predictions for total N (R^2_{pre}=0.93) and C:N ratio (R^2_{pre}=0.92). As strong creeping red fescue, slender creeping red fescue and Chewings belongs to the *F. rubra* complex while hard fescue belongs to the *F. ovina* complex, it is possible that the inclusion of species from the same complex can greatly improve the prediction of total N and N:C ratio in the calibration models.

CONCLUSION

Both the species-specific and universal (across all species) NIRS models for predicting total N were very accurate with the coefficients of determination (R^2_{cal}) greater than 0.96 and residual predictive deviation (RPD) greater than 4.0. The NIRS models were also very accurate in predicting total N of the unknown sample ($R^2_{cal} > 0.93$).

Plant cell walls composed of polysaccharides, proteins, and phenolic compounds; the prediction was less accurate than total N due to the complexity of cell wall constituents. For species-specific models, the predicting accuracy for TCW ($R^2_{cal} > 0.70$; RPD>1.7), lignocellulose ($R^2_{cal} > 0.78$; RPD>1.8) and hemicellulose ($R^2_{cal} > 0.79$; RPD>1.9) were moderately successful. A universal model across all species were less precise than species-specific models, but still acceptable for predicting TCW ($R^2_{cal} = 0.77$; RPD=2.0), lignocellulose ($R^2_{cal} = 0.86$; RPD=2.6) and hemicellulose ($R^2_{cal} = 0.75$; RPD=2.0). The NIRS models provide moderate accuracy ($R^2_{pre} > 0.70$) predicting lignocellulose and hemicellulose of unknown samples; however, the prediction of TCW, lignin, and cellulose of unknown samples was not successful.

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Table 6.1 Descriptive statistics of the cell wall constituents measured in the verdure three fine fescue species by reference method for fiber analysis.

	TCW[¶]	Lignocellulose	Hemicellulose	Lignin	Cellulose
	%				
			Mean		
Chewings (n=241)	62.3 a[†]	30.1	32.2 a	7.2 a	22.9 a
Hard (n=284)	61.2 b	30.0	31.2 b	7.8 ab	22.2 b
Strong Creeping Red (n=266)	60.1 c	30.1	30.0 c	8.3 b	21.8 c
			Standard Deviation		
Chewings	2.5	2.7	3.0	3.0	2.0
Hard	3.2	3.7	3.3	3.5	2.8
Strong Creeping Red	2.9	5.0	3.6	5.2	1.9
			Minimum		
Chewings	54.1	25.4	23.8	2.7	13.7
Hard	49.8	22.9	21.3	3.1	14.7
Strong Creeping Red	53.3	24.4	16.9	2.6	10.5
			Maximum		
Chewings	68.2	41.9	38.1	20.8	26.4
Hard	68.5	44.4	39.6	17.8	27.6
Strong Creeping Red	72.5	53.4	36.4	20.7	26.4

[¶]TCW=total cell wall content

[†]Numbers followed by the same letter(s) are not significantly different ($\alpha = 0.05$) for comparisons between species

Table 6.2 Calibration and cross-validation statistics of NIR models for predicting cell wall constituents in the verdure of three fine fescue species.

	------------- Calibration Statistics -------------			------------- Cross-validation Statistics -------------		
Constituent	Factors[†]	SEC[‡]	R^2_{cal}[¶]	SECV[f]	R^2_{cv}[€]	RPD[¥]
			Chewings (n=241)			
Total Cell Wall (%)	7	1.1	0.79	1.2	0.70	2.0
Lignocellulose (%)	6	1.0	0.78	1.2	0.69	1.8
Hemicellulose (%)	5	1.3	0.79	1.4	0.73	2.0
Lignin (%)	5	1.4	0.62	1.5	0.53	1.5
Cellulose (%)	3	1.2	0.35	1.2	0.18	1.3
			Hard (n=284)			
Total Cell Wall (%)	5	3.1	0.76	1.6	0.71	1.9
Lignocellulose (%)	9	3.3	0.91	1.2	0.86	2.8
Hemicellulose (%)	8	3.2	0.82	1.6	0.73	2.0
Lignin (%)	5	2.3	0.63	1.6	0.48	1.4
Cellulose (%)	6	2.6	0.81	1.3	0.73	2.0
			Strong Creeping Red Fescue (n=266)			
TCW (%)	6	2.5	0.76	1.5	0.69	1.8
Lignocellulose (%)	7	2.7	0.87	1.1	0.84	2.5
Hemicellulose (%)	5	2.9	0.78	1.5	0.73	1.9
Lignin (%)	3	2.4	0.76	1.2	0.72	2.0
Cellulose (%)	4	1.5	0.39	1.2	0.21	1.3
			Three Species Combined (n=791)			
TCW (%)	7	1.4	0.77	1.4	0.73	2.0
Lignocellulose (%)	9	1.1	0.86	1.1	0.83	2.6
Hemicellulose (%)	7	1.5	0.78	1.6	0.75	2.0
Lignin (%)	5	1.3	0.68	1.3	0.64	1.8
Cellulose (%)	10	1.1	0.72	1.2	0.66	1.7

[†]Number of factors used in the calibration process

[‡]Standard error of calibration (SEC)

[¶]Coefficient of determination in calibration (R^2_{cal})
[ƒ]Standard error of cross validation (SECV)
[€]Coefficient of determination in cross-validation (R^2_{cv})
[¥]Residual predictive deviation (RPD)

Table 6.3 Validation statistics of predicting cell wall constituents in verdure of fine fescue species with near infrared reflectance spectroscopy with one species omitted.

Species Omitted		R^2_{pre}†	Bias	SEP‡
Chewings (n=241)	TCW (%)	0.48	0.36	1.5
	Lignocellulose (%)	0.72	0.11	1.9
	Hemicellulose (%)	0.71	0.48	1.7
	Lignin (%)	0.58	-0.25	1.9
	Cellulose (%)	0.29	0.33	1.8
Hard (n=284)	TCW (%)	0.65	-0.08	1.1
	Lignocellulose (%)	0.70	0.23	2.1
	Hemicellulose (%)	0.69	-0.73	2.1
	Lignin (%)	0.57	0.70	2.4
	Cellulose (%)	0.53	-1.07	2.3
Strong Creeping Red (n=266)	TCW (%)	0.50	0.95	2.2
	Lignocellulose (%)	0.78	0.79	2.5
	Hemicellulose (%)	0.79	0.11	1.8
	Lignin (%)	0.64	0.96	1.5
	Cellulose (%)	0.20	0.14	1.9

†Coefficient of determination in prediction (R^2_{pre})

‡ Standard error of prediction

Table 6.4 Descriptive statistics of cell wall constituents measured in the verdure of three fine fescue species by the Dumas combustion reference method.

	Total N %	Total C %	C:N ratio
		Mean	
Chewings (n=72)	2.0 a[†]	43.0 ab	22.2 b
Hard (n=72)	1.6 b	43.2 a	29.1 a
Strong Creeping Red (n=72)	2.0 a	42.7 bc	22.7 b
Slender Creeping Red (n=72)	1.9 a	42.4 c	23.8 b
		Standard Deviation	
Chewings	0.4	0.6	4.3
Hard	0.4	1.5	7.2
Strong Creeping Red	0.5	0.8	5.8
Slender Creeping Red	0.5	1.1	6.0
		Minimum	
Chewings	1.4	41.1	13.3
Hard	1.0	35.6	15.6
Strong Creeping Red	1.3	38.9	13.2
Slender Creeping Red	1.2	37.4	13.7
		Minimum	
Chewings	3.3	44.0	30.2
Hard	2.8	46.9	44.6
Strong Creeping Red	3.3	45.0	33.7
Slender Creeping Red	3.2	44.2	35.4

[†]Numbers followed by the same letter(s) are not significantly different ($\alpha = 0.05$) for comparisons between species

Table 6.5 Calibration statistics for predicting total N, total C and the ratio of C:N by near-infrared reflectance spectroscopy in the verdure of four fine fescue species (n=284) grown in turf plots on SOIL in North Brunswick NJ from YEAR to YEAR.

	------------- Calibration Statistics -------------			------------- Cross-validation Statistics -------------		
	Factors[†]	SD[‡]	R^2_{cal}[¶]	SECV[f]	R^2_{cv}[€]	RPD[¥]
			Chewings (n=71)			
Total N (%)	6	0.4	0.98	0.1	0.97	4.0
Total C (%)	6	0.6	0.85	0.3	0.65	2.0
C:N ratio	3	4.0	0.95	1.0	0.82	4.0
			Hard (n=68)			
Total N (%)	4	0.4	0.97	0.1	0.95	4.0
Total C (%)	3	0.9	0.39	0.7	0.23	1.3
C:N ratio	6	7.0	0.98	1.5	0.95	4.7
			Strong Creeping Red (n=72)			
Total N (%)	6	0.5	0.99	0.1	0.98	5.0
Total C (%)	6	0.6	0.79	0.4	0.49	1.5
C:N ratio	3	5.7	0.97	1.1	0.93	5.2
			Three Species Combined (n=211)			
Total N (%)	7	0.5	0.99	0.1	0.98	5.0
Total C (%)	7	0.8	0.75	0.4	0.66	2.0
C:N ratio	5	5.7	0.96	1.3	0.95	4.4

[†]Number of factors used in the calibration process
[‡]Standard error of calibration (SEC)
[¶]Coefficient of determination in calibration (R^2_{cal})
[f]Standard error of cross validation (SECV)
[€]Coefficient of determination in cross-validation (R^2_{cv})
[¥]Residual predictive deviation (RPD)

Table 6.6 Effect of omitting one species on validation statistics for predicting total N, and total C and the ratio of C:N by near infrared reflectance spectroscopy in the verdure of four fine fescue species (n=284) grown in turf plots on loam in North Brunswick NJ from 2015 to 2016

		R^2_{pre} †	Bias	SEP ‡
Chewings (n=71)	Total N (%)	0.97	0.02	0.1
	Total C (%)	0.76	0.39	0.5
	C:N ratio	0.95	-0.53	1.4
Hard (n=68)	Total N (%)	0.93	0.04	0.1
	Total C (%)	0.50	0.35	1.2
	C:N ratio	0.92	1.8	3.7
Strong Creeping Red Fescue (n=72)	Total N (%)	0.99	0.02	0.1
	Total C (%)	0.64	-0.07	0.5
	C:N ratio	0.97	-0.25	1.2

†Coefficient of determination in prediction (R^2_{pre})
‡Standard error of prediction

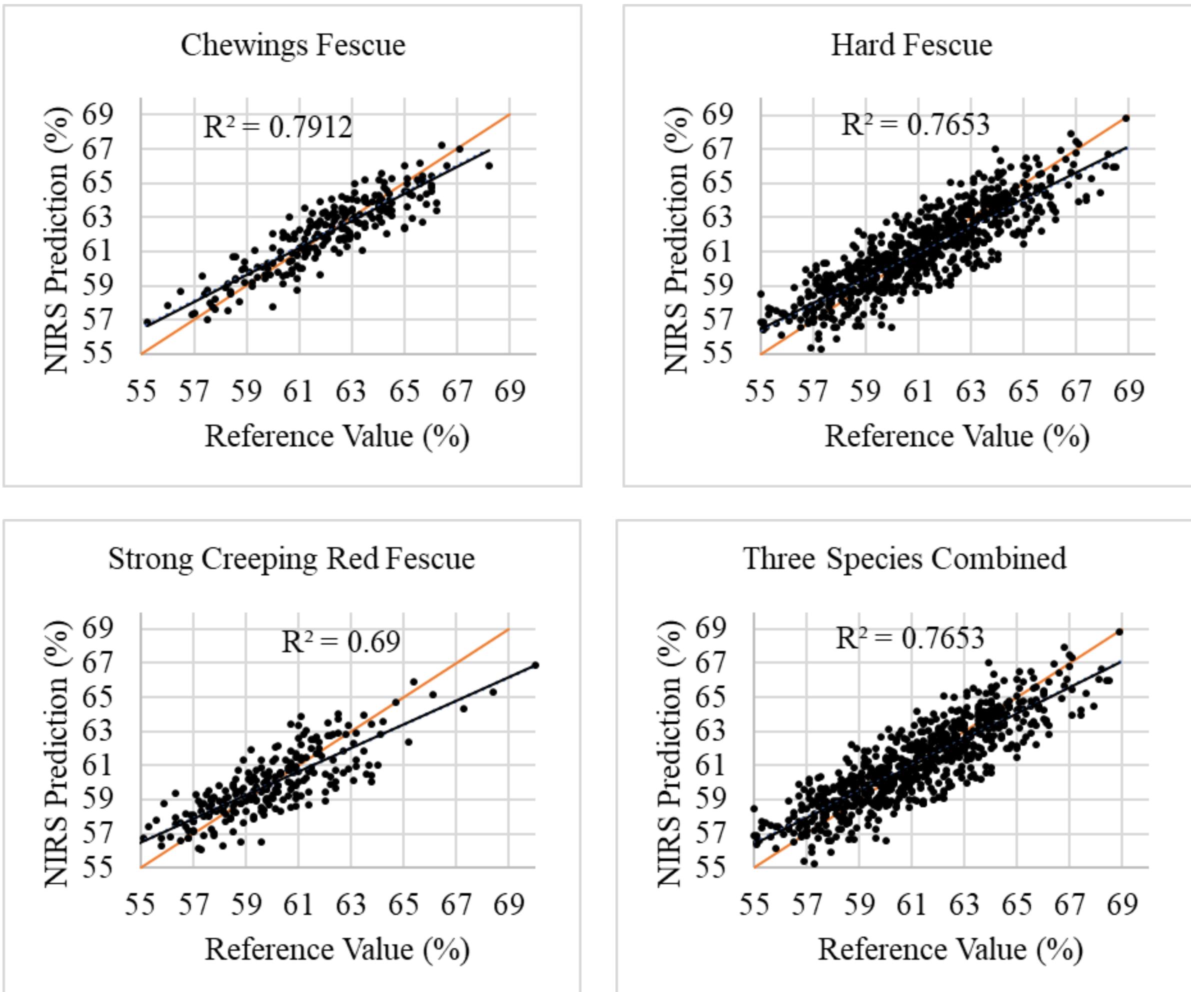

Figure 6.1 Linear regression fit NIRS predicted value over reference value for **total cell wall** on Chewings fescue, hard fescue, strong creeping red fescue, and all three species combined. The black line represents the regression line; the value R^2 denotes the coefficient of determination. The orange line represents perfect agreement between NIRS predicted value and reference value.

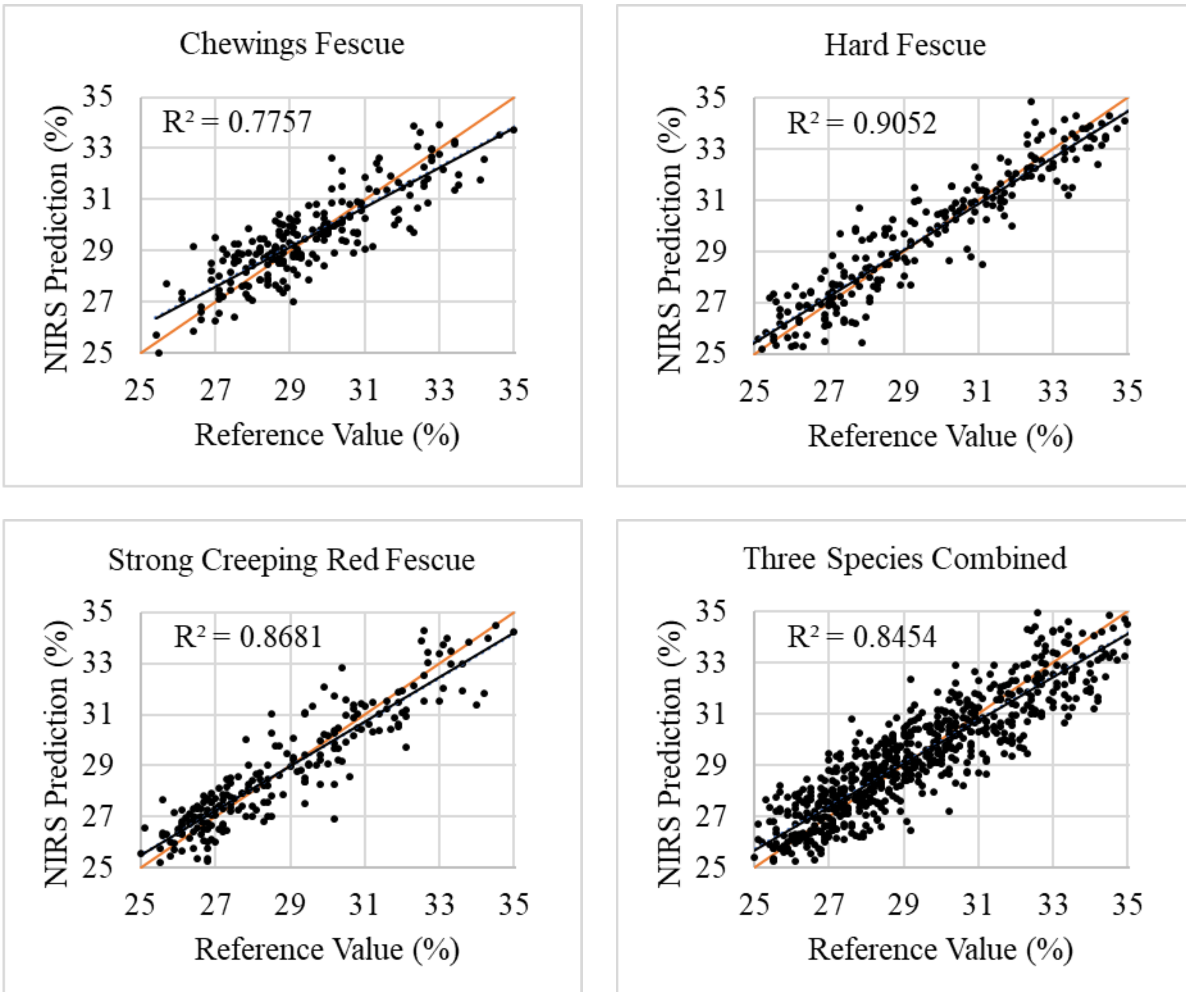

Figure 6.2 Linear regression fit NIRS predicted value over reference value for **lignocellulose** on Chewings fescue, hard fescue, strong creeping red fescue, and all three species combined. The black line represents the regression line; the value R^2 denotes the coefficient of determination. The orange line represents perfect agreement between NIRS predicted value and reference value.

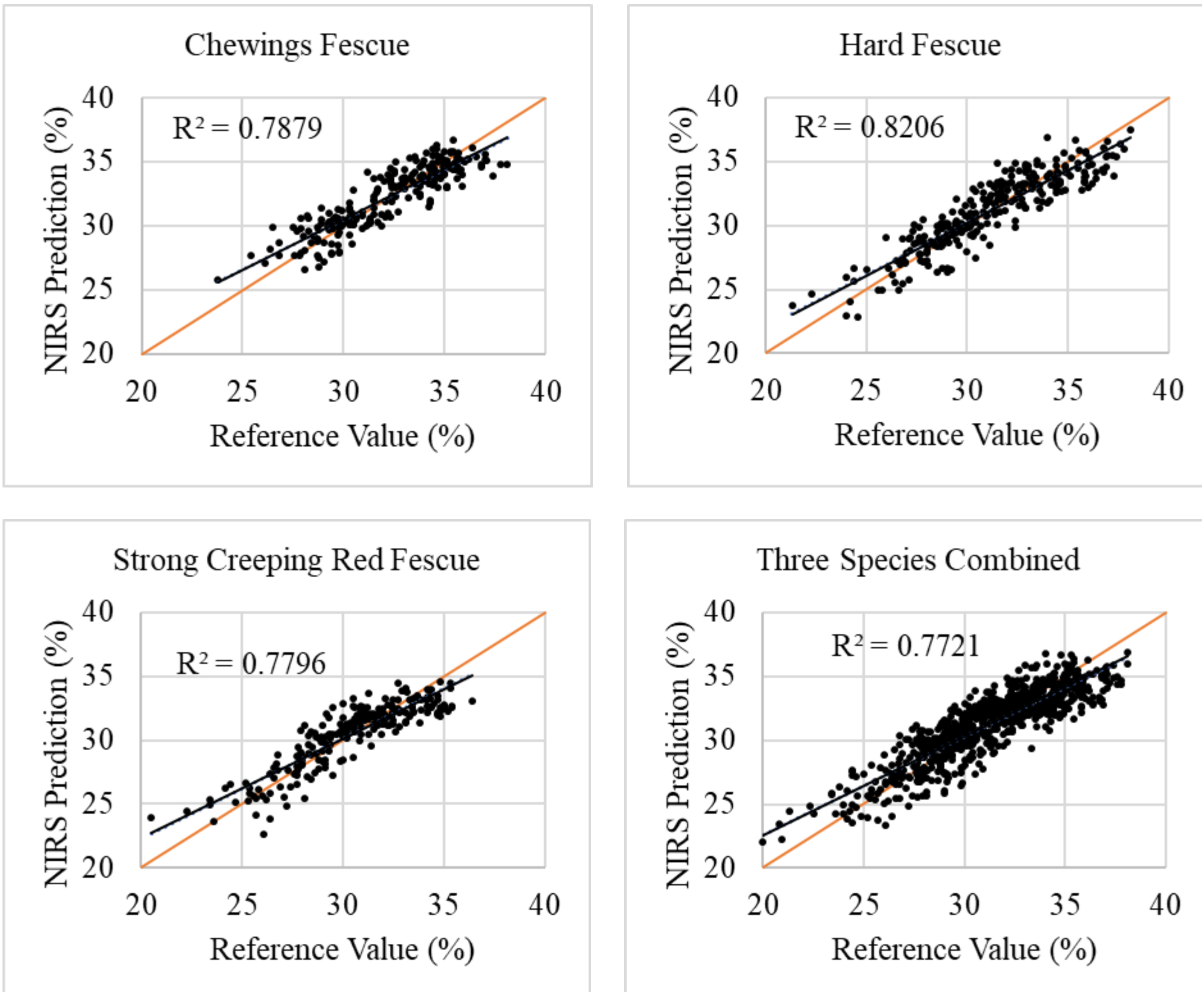

Figure 6.3 Linear regression fit NIRS predicted value over reference value for **hemicellulose** on Chewings fescue, hard fescue, strong creeping red fescue, and all three species combined. The black line represents the regression line; the value R^2 denotes the coefficient of determination. The orange line represents perfect agreement between NIRS predicted value and reference value.

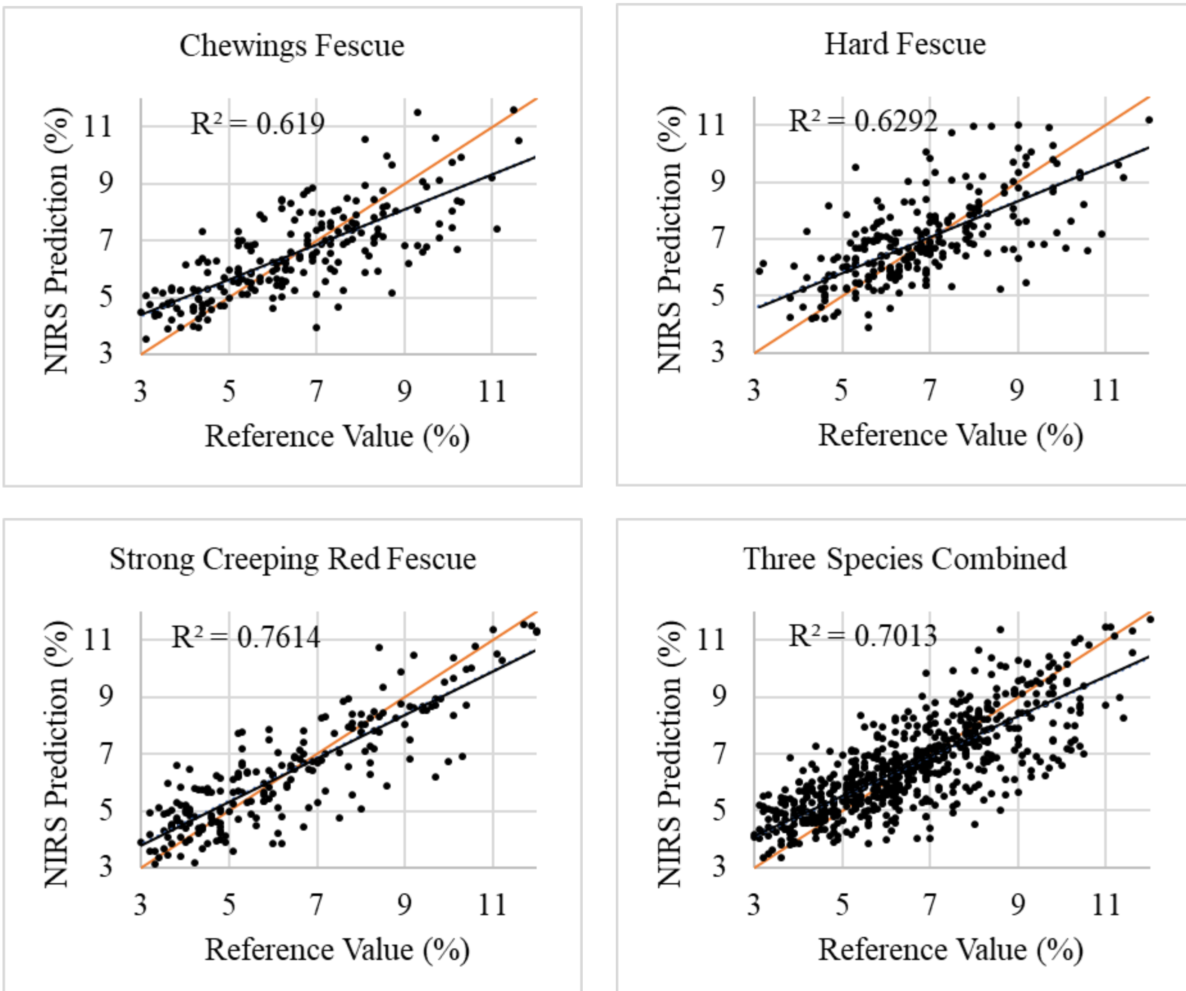

Figure 6.4 Linear regression fit NIRS predicted value over reference value for **lignin** on Chewings fescue, hard fescue, strong creeping red fescue, and all three species combined. The black line represents the regression line; the value R^2 denotes the coefficient of determination. The orange line represents perfect agreement between NIRS predicted value and reference value.

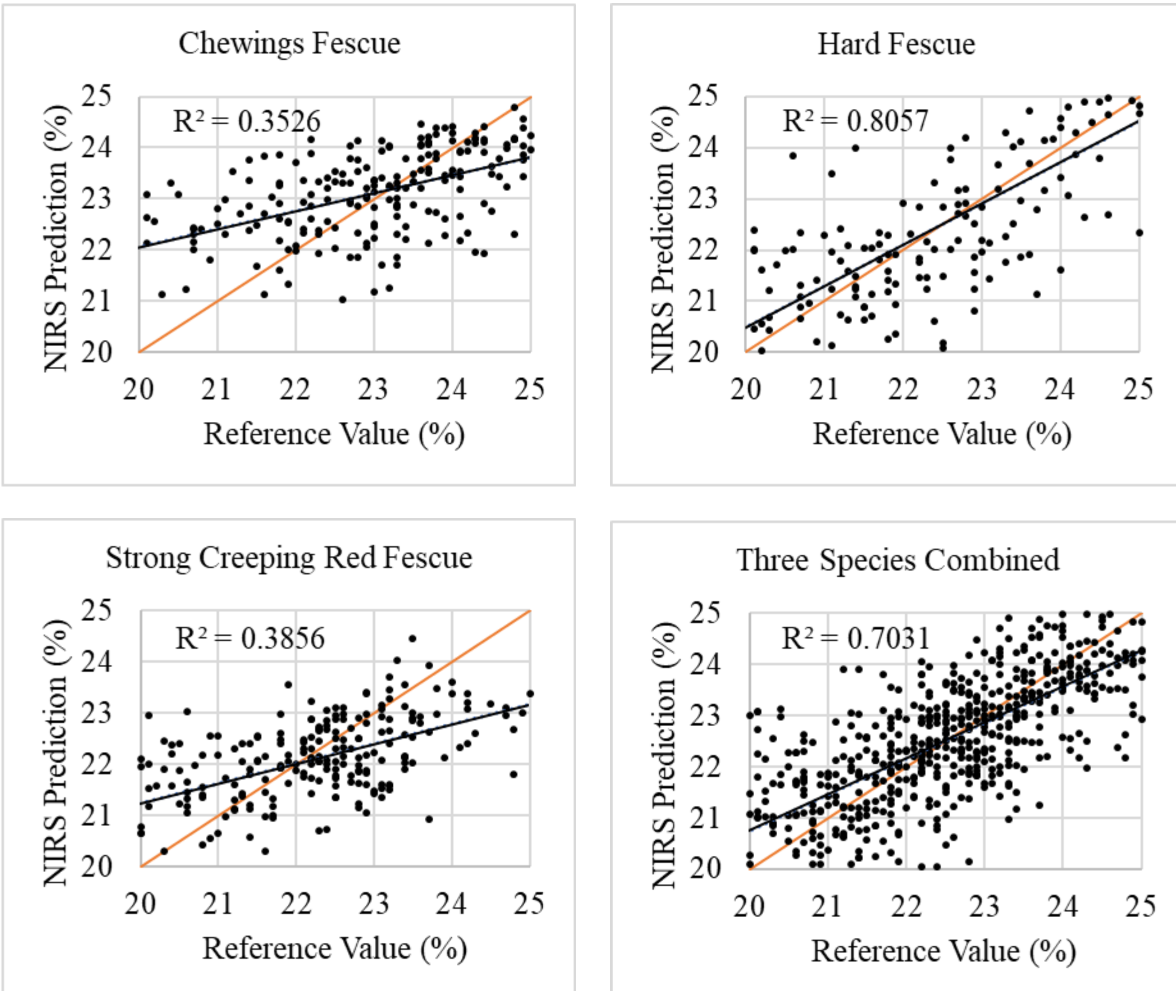

Figure 6.5 Linear regression fit NIRS predicted value over reference value for **cellulose** on Chewings fescue, hard fescue, strong creeping red fescue, and all three species combined. The black line represents regression line, the value R^2 denotes coefficient of determination. The orange line represents perfect agreement between NIRS predicted value and reference value.

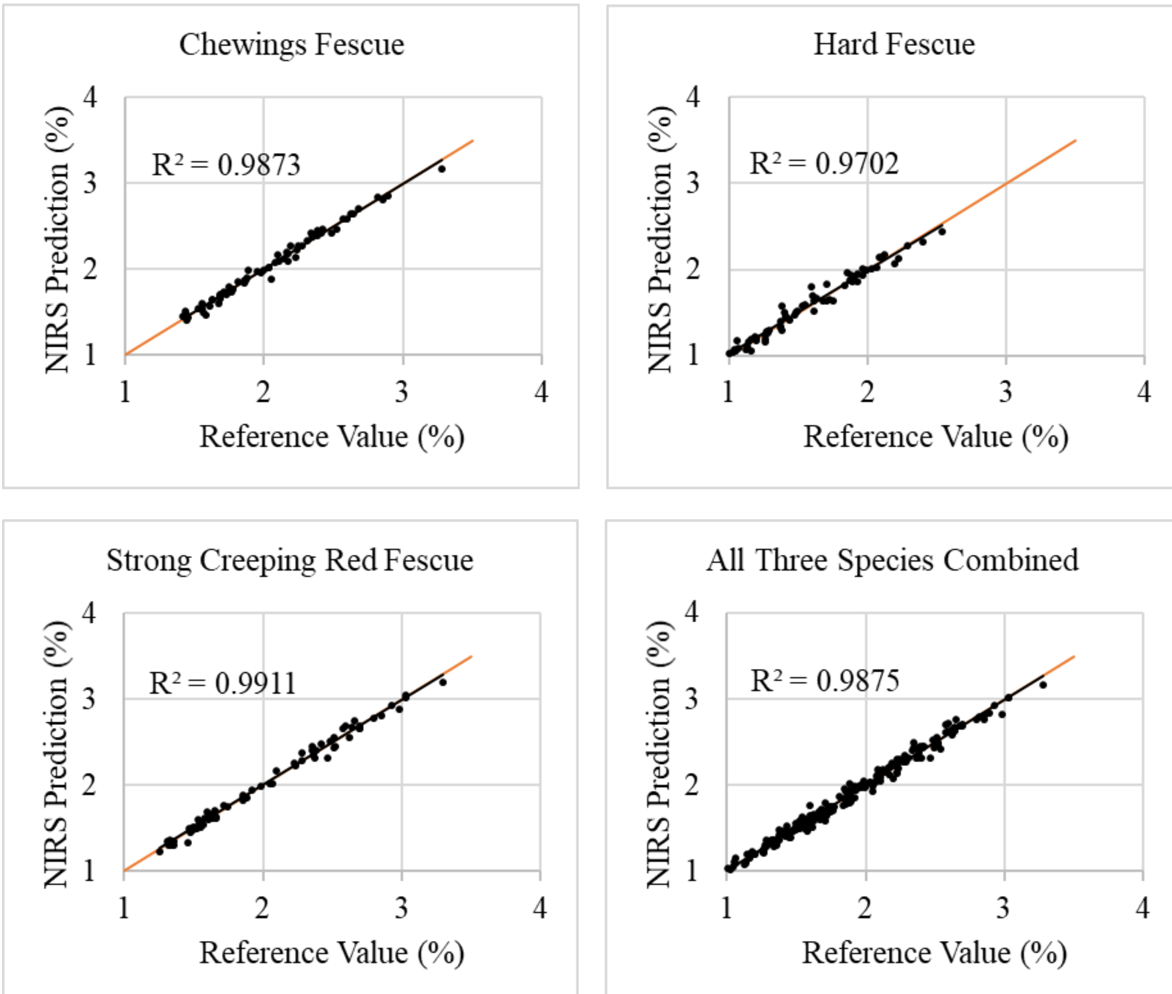

Figure 6.6 Linear regression fit NIRS predicted value over reference value for **total nitrogen (N)** on Chewings fescue, hard fescue, strong creeping red fescue, and all three species combined. The black line represents regression line, the value R^2 denotes coefficient of determination. The orange line represents perfect agreement between NIRS predicted value and reference value.

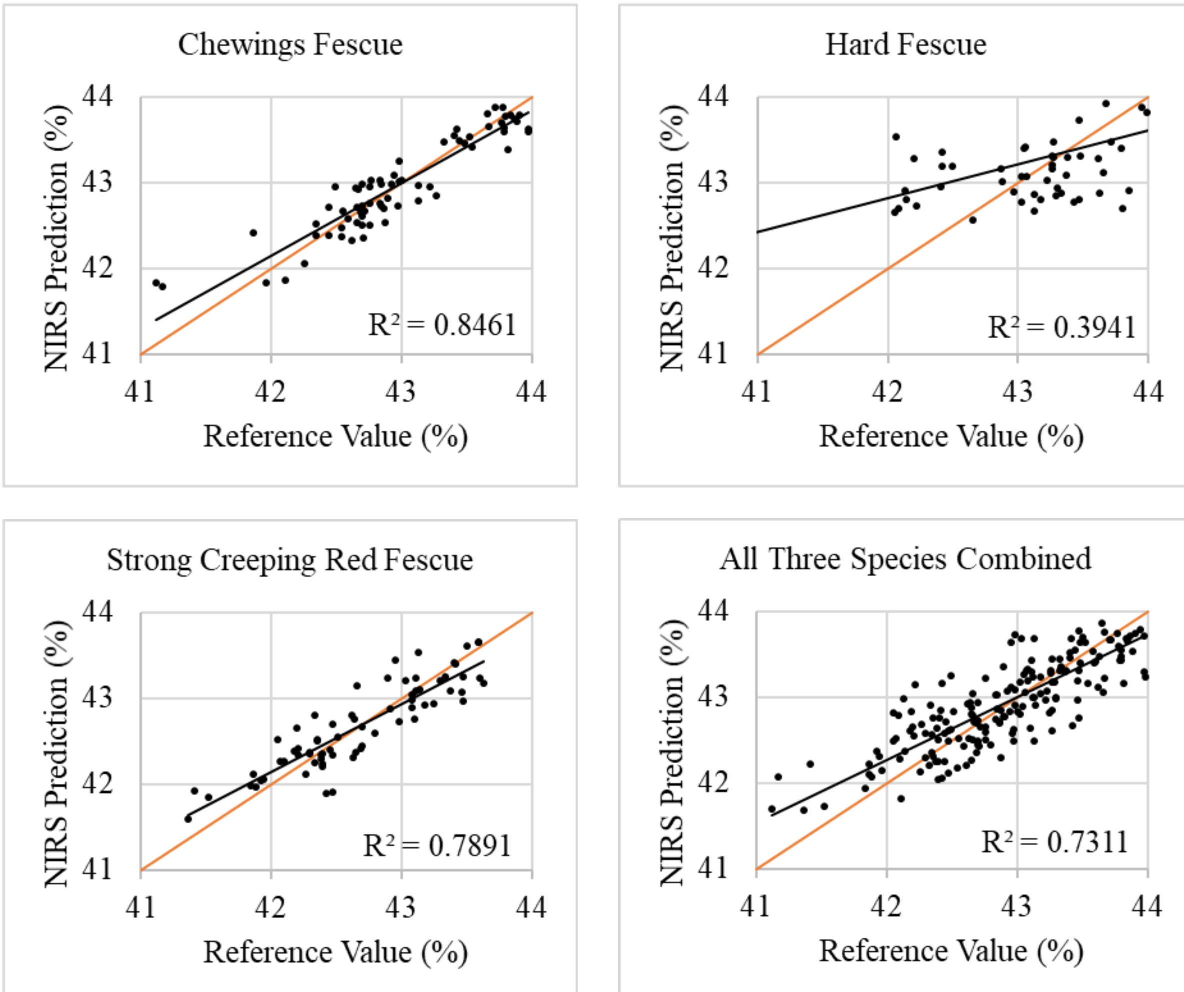

Figure 6.7 Linear regression fit NIRS predicted value over reference value for **total carbon (C)** on Chewings fescue, hard fescue, strong creeping red fescue, and all three species combined. The black line represents regression line, the value R^2 denotes coefficient of determination. The orange line represents perfect agreement between NIRS predicted value and reference value.

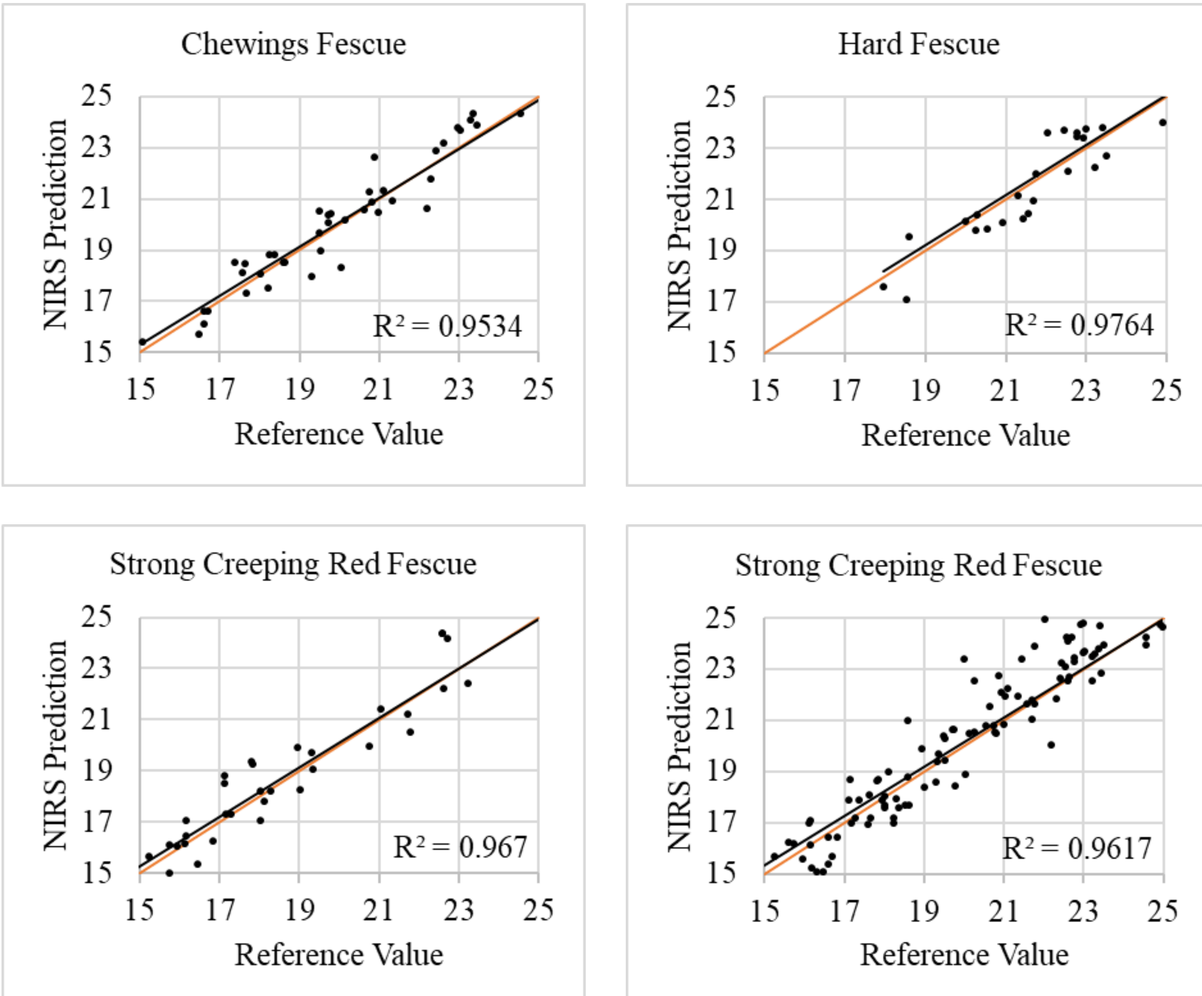

Figure 6.8 Linear regression fit NIRS predicted value over reference value for **C:N ratio** on Chewings fescue, hard fescue, strong creeping red fescue, and all three species combined. The black line represents regression line, the value R^2 denotes coefficient of determination. The orange line represents perfect agreement between NIRS predicted value and reference value.

CHAPTER 7 Correlations between Verdure Biomass and Concentration of Cell Wall Constituents with Fine Fescue Wear Tolerance

ABSTRACT

Fine fescues (*Festuca* spp.) are not utilized to the same extent as other cool-season turfgrass species partly due to a lower tolerance of wear and slower recuperative ability after damage. There is a need to develop screening protocols to select wear-tolerant cultivars using the concentration of cell wall constituents as a predictor. However, limited data are available regarding the mechanisms responsible for enhanced wear tolerant fine fescues. This field research was undertaken to i) assess overall wear tolerance of three major fine fescue species, Chewings, hard, and strong creeping red fescue; and ii) determine the relationship of verdure biomass and cell wall composition with wear tolerance within and between these species. Evaluations were conducted in three locations on both turf plot and genotype tillers using two traffic simulators. Verdure samples were collected from non-trafficked turf plots or tillers to determine verdure biomass and concentration of cell wall constituents. Considerable intra- and inter-specific variation in wear tolerance, verdure biomass and cell wall composition were evident, which allowed the investigation of wear tolerance mechanisms within and across fine fescue species. As a group, Chewings fescues and hard fescue were more wear tolerant and produced greater verdure biomass and concentration of cell wall constituents than strong creeping red fescue. A general correlation between verdure biomass, cell wall constituents and wear tolerance were identified at the inter-specific level. Correalations were also significant at intra-specific levels for Chewings and strong creeping red fescue;improved wear tolerance of these species was associated with

greater verdure biomass, TCW and lignocellulose concentration and reduced lignin concentration. However, the correlations between verdure biomass and cell wall constituents to wear tolerance were not well detected within hard fescue due to the genetic and biologically similarity among hard fescue entries tested in this study.

INTRODUCTION

Fine fescues (*Festuca* spp.) are a group of cool-season turfgrass species that are tolerant to drought and shade stresses and require less water and fertilizer compared to other commonly used cool-season species (Bonos and Huff, 2013). Three of the fine fescue species most widely used for turfgrass areas are Chewings fescue (*F. rubra ssp. commutata*), hard fescue (*F. brevipila*), and strong creeping red fescue (*F. rubra ssp. rubra*). However, these species are not utilized to the same extent as other cool-season turfgrass species partly due to a lower tolerance of wear and slower recuperative ability after damage.

Turfgrasses are different than other crops as they can form and maintain ground cover under regular mowing and wear. Plant cell walls provide mechanical support for aerial shoots as well as resistance to diseases, insects, cold temperatures, and other stresses (Rhodes, 1985). Numerous studies indicated that cell wall constituents were important in determining wear tolerance of turfgrass. Shearman and Beard (1975a) reported that wear tolerance of seven cool-season turfgrass species was positively correlated with total cell wall content (TCW) expressed on a weight per unit area basis, percentage verdure, and percentage chlorophyll. Canaway (1981) proposed using verdure biomass as a more reliable predictor for wear tolerance due to inconsistent correlations between cell wall constituents and wear tolerance.

Studies at the intra-specific level on both cool- and warm-season species indicated the relationships between cell wall constituents and wear tolerance varies with species (Bourgoun et al. 1985; Brosnan et al., 2005; Dowgiewicz et al., 2011; Kilmartin, 1994; Trenholm et al. 2000). There is limited information available regarding the correlation between cell wall constituents and wear tolerance in fine fescues. Should meaningful relationships exist, there would be potential to use cell wall constituent as a screening protocol to reliably select wear-tolerant germplasm. Thus, the objectives of this study were i) to evaluate relationships between wear tolerance and verdure biomass, and cell wall constituents at both intra- and inter-specific levels for Chewings, hard and strong creeping red fescues.

MATERIALS AND METHODS

Site Description and Maintenance

Study 1: Wear Tolerance Field Trial (Adelphia, NJ)

This study was seeded as a randomized complete block design with 3 replications on September 18, 2014, at the Rutgers Plant Biology Research and Extension Station in Adelphia, NJ. The soil type was Freehold sandy loam (fine-loamy, mixed, active, mesic Typic Hapludults). Plots were 0.9- x 1.5-m in size and seeded at a rate of 17.9 g m^{-1}. This trial was maintained at a 6.35 cm mowing height with a rotary mower. The annual nitrogen (N) rates were 48.8 kg ha^{-1} with two application dates in April and September from 2014 to 2017. Irrigation was applied to prevent severe drought stress. This study received applications of mesotrione + 0.25% v/v non-ionic surfactant at sowing at a rate of 0.42 g a.i. ha^{-1} and followed by an application of 0.28 kg a.i. ha^{-1} + 0.25% v/v non-ionic surfactant 28 days after seedling emergence to the entire field trial area (Tate, 2019). Broadleaf weeds were controlled by dithiopyr and 2,4-Dichlorophenoxyacetic acid applied at 0.11 and 0.54 kg a.i. ha^{-1}, respectively, on 29 April and 2 June in 2015 and 21 in 2016. No pesticides were applied in 2017. Plots with severe weed encroachment were excluded from wear evaluation.

Abrasive wear was applied with Rutgers Wear Simulator (RWS), a 0.8-m wide simulator with rubber paddles mounted on a Toro landscape mower designed to impart wear to aboveground plant parts and minimize soil compaction (Bonos et al., 2001). The RWS was operated at 4.0 km h^{-1} with paddles rotating at 250-rpm. Twenty-four passes (four passes per week) of abrasive wear were applied to from 3 October to 9 November 2017. Abrasive wear was applied to one-half of plot and verdure samples were collected from the non-worn half of 59 fine fescue entries (20 Chewings fescue, 26 hard fescues, 13 strong creeping red fescues) on 5 October 2017 for fiber analysis. Sampled areas were measured to determine verdure biomass. Uniformity of turf cover (UTC; 1 to 9 scale, 9=most uniform turf cover) and fullness of turf canopy (FTC; 0-100% scale, 100%=full canopy) were visually assessed on both non-worn and worn grass before the initiation and at the conclusion of wear.

Study 2: Wear Tolerance Field Trial (North Brunswick, NJ)

This study was seeded into 0.9- x 1.5-m plots as a randomized complete block design with three replications in September 2012 on a Nixon loam (fine-loamy, mixed, mesic Typic Hapludults) at Hort. Farm 2 in North Brunswick, NJ. This trial was maintained at a 6.35-cm mowing height and followed the same maintenance as described in Chapter one. Plots were inoculated with 8.6 g m^{-2} of a 50:50 mixture of oats infested with *Microdochium nivale* isolates PPCC12012 and PP42013 on 3 December 2015 and 1 December 2016 and covered with two layers of a permeable growth cover. Plots with residual disease damage were excluded from wear evaluation.

Abrasive wear was applied with RWS operated at 4.0 km h^{-1} with paddles rotating at 250-rpm. Twenty-four passes (four passes per week) of abrasive wear were applied to from 4 June to 9 July 2017. Abrasive wear was applied to one-half of the plot, and verdure samples were collected from the non-worn half of 52 fine fescue entries (16 Chewings fescue, 14 hard fescue entries, 22 strong creeping red fescues) on 5 October 2017 for fiber analysis. Sampled areas were measured to determine verdure biomass. Uniformity of turf cover (UTC; 1 to 9 scale, 9=most uniform turf cover) and fullness of turf canopy (FTC; 0-100% scale, 100%=full canopy) were visually assessed on both non-worn and worn grass before the initiation and at the conclusion of wear.

Study 3: Wear Tolerance Tiller Plots (North Brunswick, NJ)

Individual genotypes of Chewings fescue (157 total), hard fescue (155) and strong creeping red fescue (149) were selected from several commercial cultivars and improved breeding material from the turfgrass breeding program at Rutgers University, New Jersey Agricultural Experiment Station (Grimshaw et al., 2018). Single tillers were propagated from each genotype and then transplanted on a Nixon loam (fine-loamy, mixed, mesic Typic Hapludults) at Hort. Farm 2 in North Brunswick, NJ in June of 2014 using a randomized complete block design with 6 replications. The trial was maintained at 7.62-cm mowing height and irrigation was applied as needed to ensure the establishment and avoid severe drought stress. Fertilization and pesticide application record was described by Grimshaw et al. (2018).

Wear tolerance of fine fescue entries were assessed by applying 26 passes of RWS (four passes per week with two additional passes at the end for greater wear tolerance separation) from 12 June to 24 July 2018. Abrasive wear was applied to three out of six replications, and turf quality was visually assessed based on a 1-10 scale (10 = no effect, 1= clone death) at the conclusion of wear treatment. A total of 184 genotypes (61 Chewings fescues, 61 hard fescues, 62 strong creeping red fescues) were selected to represent a broad range in wear tolerance within each species. Verdure samples of selected genotypes were collected on 27 July 2018 from three non-worn replications for fiber analysis.

Study 4: Traffic Tolerance Tiller Plots (St. Paul, MN)

The genotypes described above for Study 3 were planted on a Waukegan silt loam (fine-silty over sandy, mixed, mesic Typic Hapludoll) at the Turfgrass Research, Outreach, and Education Center at the University of Minnesota in St. Paul, MN in June 2014. This trial was maintained at 7.62-cm mowing height and irrigated to avoid severe drought stress. Fertilization and pesticide application record was described by Grimshaw et al. (2018).

Fine fescue clones were trafficked with a custom-built golf cart traffic simulator towed behind a turf utility vehicle (Watkins et al., 2010). The traffic simulator consisted of two 454-kg traffic units on an axle containing five golf cart tires, which imparted both wear and soil compaction to the turf but less wear than the Rutgers Wear Simulator (Alderman, 2016).

Traffic tolerance of fine fescue entries was assessed by applying 24 passes of golf cart traffic simulator (four passes per week) from 15 June to 27 July 2018 on three out of six replications. Turf quality was visually assessed based on a 1-10 scale (10 = no effect, 1= clone death) at the conclusion of wear treatment. Clones with severe weed encroachment were excluded from the traffic tolerance evaluation. A total of 113 genotypes (51 Chewings fescue, 39 hard fescues, 23 strong creeping red fescues) were selected. The verdure of the selected genotypes was collected 27 July 2018 from three non-worn replications for fiber analysis.

Sample Preparation and Fiber Analysis

Verdure samples were collected using a grass shear (GARDENA CANADA LTD., Brampton, ON, Canada) and dried at 70 °C for 72 hours. Verdure biomass (kg m^{-2}) was calculated using dry weight (kg) divided by the sampling area (m^{-2}). Dry samples were ground (Wiley Mill, Thomas Scientific, Swedesboro, NJ) to pass a 1-mm sieve.

Samples collected from study one and study two were subjected to fiber analysis to determine percent cell wall constituents on a dry weight basis (Goering and Van Soest, 1963). The neutral detergent fiber (NDF) procedure determined TCW concentration and the acid detergent fiber (ADF) determined lignocellulose concentration on a dry weight basis. The difference between the quantity of NDF and ADF estimated hemicellulose concentration. The acid detergent lignin (ADL) was used to determine the lignin concentration, and the difference between ADF and ADL estimated cellulose concentration. Cell wall constituents (TCW, lignocellulose, hemicellulose, lignin, and cellulose) were also calculated as dry weight per unit area (g dm^{-2}) by multiplying the fraction of each cell wall constituent (g kg^{-1}) by biomass (kg m^{-2}). Cell wall constituents of samples collected from Study 3 and Study 4 were determined using a universal near-infrared spectroscopy (NIRS) model developed in Chapter 5 with the R^2_{cal} for the flowing constituents: total cell wall (0.77), lignocellulose (0.86), hemicellulose (0.78), lignin (0.68), and cellulose (0.72).

Data Analysis

Due to differences in the type and intensity of wear or traffic that were applied, data were analyzed separately for each study. Statistical analysis was carried out using the Statistical Analysis System (SAS) software package (v. 9.4: SAS Institute), and data were subjected to nested analysis of variance (ANOVA) using the generalized linear model (GLM) procedure. The null hypotheses for nested ANOVA were i) three fine fescues have the same mean; ii) cultivars within each species have the same mean. Fisher’s protected least significant difference test at the 0.05 probability level was used to test for difference among species.

Multiple regression analysis was performed to determine the relationship between wear tolerance to verdure biomass, and concentration of TCW, lignocellulose, and lignin measured on field plots (study 1 and 2) and tiller clones (study 3 and 4). Hemicellulose (TCW-lignocellulose) and cellulose (lignocellulose-lignin) were excluded from the model to avoid multicollinearity. A full model was first developed including all the predictors (verdure biomass, TCW, lignocellulose, and lignin). A final model was then developed using the stepwise selection method. The stepwise selection combines the forward-selection and backward-elimination steps. Variables entered the final model with an F ratio set to 4 and α set to 0.15, and variables stayed in the model with α set to 0.05. Thus, all independent variables included in the final model were significant at the 0.05 level. Final models were assessed by partial R^2 to determine the relative contribution of an independent variable in accounting for the total variation in wear tolerance.

RESULTS AND DISCUSSION

Response of fine fescue species to wear or traffic simulation

The response to wear differed among the three fine fescue species and the differences among cultivars within species were also detected (Table 7.1). In study 1, hard fescue had the greatest average UTC (7.1) and FTC (79) ratings, followed by Chewings fescue (UTC=3.8 and FTC=49), and strong creeping red fescue had the lowest average ratings (UTC=1.5 and FTC=19). In study 2, Chewings fescue had the greatest UTC (3.9) and FTC (39); hard fescue had intermediate UTC (2.8) and FTC (30) ratings while strong creeping red fescue had the lowest UTC (2.1) and FTC (22). The tiller quality of Chewings fescue (4.9) and hard fescue (4.1) were greater than strong creeping red fescue (3.1) under wear in study 3. These results were similar to the findings of Shildrick et al. (1975), who reported that Chewings fescues were more wear tolerant than strong creeping red fescues in monocultures and in mixtures with perennial ryegrass. Bonos et al. (2001) and Grimshaw et al. (2018) also reported improved wear tolerance with Chewings fescue and hard fescue compared to strong creeping red fescue. Cross et al. (2013) attributed the improvement of wear tolerance to the increased breeding and selection of hard fescue and Chewings fescue during the early 2000s.

Analysis of variance indicated that the responses of fine fescue to tire-traffic in study 4 differed at the cultivar level but not species level. The difference among cultivars under tire-traffic was less evident than under abrasive wear. The result confirms the findings reported in Chapter 1, which indicated abrasive wear was more effective in distinguishing levels of wear tolerance in fine fescues.

Verdure biomass and cell wall constituents of fine fescues

Species main effect was significant on verdure biomass of non-trafficked turf- or tiller-plots (Table 7.2). Hard fescue had greater verdure than Chewings fescue, which had greater verdure than strong creeping red fescue in studies 1, 2, and 3; however, there was no significant difference among cultivars or genotypes within species. In study 4, Chewings fescue had the greater verdure biomass than hard fescue while strong creeping red fescue had the lowest verdure biomass.

Significant differences in cell wall constituents (TCW, lignocellulose, hemicellulose, lignin, and cellulose) were observed at the species levels as well as among cultivars and genotypes within species (Tables 7.3 and 7.4). The wear-tolerant species, Chewings fescue and hard fescue, exhibited significantly greater TCW concentration compared to the wear-intolerant strong creeping red fescue. The average TCW concentration for Chewings fescue ranged from 59.9% to 64.6%; hard fescue ranged from 59.4% to 62.3%, and strong creeping red fescue ranged from 56.5% to 60.2%. A similar ranking was observed for concentration of lignocellulose and hemicellulose, while the rankings for lignin and cellulose content were less consistent.

These results were similar to studies comparing cell wall constituents at inter-specific levels (Canaway, 1981; Shearman and Beard, 1975b). Shearman and Beard (1975b) found greater TCW and cellulose content in ‘Cascade’ Chewings fescue than ‘Pennlawn’ strong creeping red fescue when measured on a dry weight basis; however, the ranking reversed when TCW and cellulose content on weight per unit area basis (g dm^{-2}). Canaway (1981) found greater lignocellulose content in ‘Highlight’ Chewings fescue than ‘Boreal’ strong creeping red fescue. The author also indicated that the ranking of cell wall content when expressed on a weight per unit area basis (g dm^{-2}) largely followed the same pattern as for biomass due to the fact that differences among species in biomass were much greater than the relatively small differences in the concentration of cell wall constituents.

Correlation between traffic tolerance and fine fescue traits

The results of correlation coefficients (r) of field plot wear tolerance, and the biomass and cell wall constituents of verdure of non-trafficked portion of the plot for study 1 and 2 were summarized in tables 7.5 and 7.6, respectively.

In study 1 (Table 7.5; Figure 7.1 and 7.2), verdure biomass was positively correlated with wear tolerance (measured as UTC and FTC) of fine fescues at the inter-specific level. Results also suggested wear tolerance of fine fescues at the inter-species level was positively correlated with TCW, lignocellulose, and cellulose, while negatively correlated with lignin (Table 7.5). The correlation was also observed on the intra-specific level for Chewings and strong creeping red fescues but less significant (Table 7.5). The weaker correlation on the intra-specific level compared to the inter-specific level was due to the narrow phenetic difference within each species. As a group, hard fescues had the greatest verdure biomass and UTC followed by Chewings fescue, while strong creeping red fescue was the lowest. The scatter plot (Figure 7.1) of verdure biomass and UTC of study 1 illustrates this phenomenon. A positive correlation was very clear when including all three species, while the correlation was less clear within each species due to the similarity of their verdure biomass as well as wear tolerance. A similar trend was observed between TCW and UTC (Figure 7.2).

In study 2 (Table 7.6; Figure 7.3 and 7.4), TCW, lignocellulose, and hemicellulose were positively correlated with wear tolerance parameters at the inter-specific level but at the intra-species level, these parameters were only correlated with wear tolerance in Chewings fescue (Table 7.6). The strongest correlations were observed for TCW with r ranging from 0.72 to 0.76. Verdure biomass was positively correlated with wear tolerance at the inter-specific level but not at the intra-specific level. Lignin was not correlated with wear tolerance in study 2, and significant correlations of wear tolerance with cellulose were not strong at the inter-specific levels. Results

The results of correlation coefficients (r) between the quality of tiller-plots subjected to traffic and the biomass and cell wall constituents of verdure sampled from non-trafficked tiller-plots in study 3 and study 4 were summarized in tables 7.7 and 7.8, respectively.

In study 3 (Table 7.7; Figure 7.5 and 7.6), biomass, TCW, and hemicellulose were positively correlated with tiller-plot quality at the inter-specific level as well as the intra-specific level for Chewings fescue and strong creeping red fescue (Table 7.7). At the intra-specific level of hard fescue, tiller quality was positively correlated with verdure biomass (r=0.61) and cellulose content (r=0.51) but negatively correlated with lignin content (r=-0.43).

In study 4 (Table 7.8; Figure 7.7 and 7.8), significant correlations between tiller-plot quality and biomass, TCW, lignocellulose, lignin, and cellulose were limited to intra-specific relationships in Chewings fescue; positive for biomass, TCW, lignocellulose and cellulose and negative for lignin (Table 7.8). Cellulose content was positively correlated with tiller-plot quality in hard fescue and at the inter-specific level. The golf cart traffic simulator was not as effective as the RWS in differentiating the traffic tolerance of fine fescues which resulted in poor correlation.

Studies of wear tolerance on other species have reported positive correlations with non-trafficked turf quality and shoot density (Trenholm et al., 2000; Bonos et al., 2001; Cashel et al., 2005; Samaranayake et al., 2008; Park et al., 2009). In this study, increased verdure biomass was associated with improved wear and traffic tolerance of fine fescues at both the intra- and inter-specific levels. Previous studies have reported positive correlations between verdure biomass and wear tolerance within and across Kentucky bluegrass (*Poa pratensis*), perennial ryegrass (*Lolium perenne*), bentgrass (*Agrostis* spp.) and fine fescue species (Bourgoin et al., 1985; Canaway, 1981; Dowgiewicz et al., 2011). A similar trend was also reported by Trenholm et al. (2000) on warm-season seashore paspalum (*Paspalum vaginatum*) and bermudagrass (*Cynodon dactylon*). Positive correlations between shoot density and wear tolerance are thought to be a result of a greater quantity of shoot tissue available to absorb the impact of traffic forces (Trenholm et al., 2000).

Positive correlations between wear tolerance and cell wall components, including TCW, lignocellulose, hemicellulose, and cellulose, were observed both within and across three fine fescue species. The TCW and lignocellulose content of Kentucky bluegrass cultivars was positively correlated with wear tolerance (Brosnan et al., 2005). Similar results have been reported in studies on both cool-season and warm-season turf species (Bourgoin et al., 1985; Dowgiewicz et al., 2011; Kilmartin, 1994; Roche et al., 2009). Conversely, wear tolerant perennial ryegrass cultivars were negatively correlated with TCW content in a greenhouse trial (Den Haan et al., 2004). Trenholm et al. (2000) reported a negative correlation between TCW content and wear tolerance in seashore paspalum and cellulose content and wear tolerance in bermudagrass. Thus, anatomical, morphological, and physiological factors for wear tolerance needs to be evaluated at the species level to ensure screening accuracy.

In the current study, there were similarities in the association between TCW, lignocellulose, and cellulose to wear tolerance at the intra- and inter-specific levels. This outcome indicates that cell wall constituents could be useful as a screening criterion for the enhancement of wear tolerance within and across fine fescue species. However, the

Multiple linear regression

Full multiple linear regression models using verdure biomass and the concentration of TCW, lignocellulose, and lignin to identify relationships with wear tolerance for each fine fescue species and across three species. Final multiple linear regression models developed based on a reduced number of independent variables achieved R^2 values similar to full models and were significant at the 0.05 probability level (Table 7.9). Considerable intra- and inter-specific variation in wear tolerance was present in fine fescue species, and this variation was largely explained by verdure biomass and TCW.

In study 1, verdure biomass was the principal predictor explaining 74.6% of the variation in UTC and 70.0% of the variation in UTC at the inter-specific level. Within strong creeping red fescues, verdure biomass also accounted for 45.1% of the variation in UTC and 48.1% of the variation in FTC, while lignin content contributed 26.3% and 25.3% of the total variation in UTC and FTC, respectively (Table 7.8).

In study 2, TCW was the only significant predictor for the inter-specific models, which contributed 53.0% of the variation in UTC and 52.3% of the variation in FTC (Table 7.9). Similarly, TCW was the principal predictor in explaining the total variation of UTC (57.4%) and FTC (52.3%) in Chewings fescue (Table 7.10).

Shearman and Beard (1975b) reported that the effects of all cell wall constituents expressed on a weight per unit area basis (R^2= 97%) and on a dry weight basis (R^2= 96%) were the best criteria to estimate wear tolerance on inter-specific levels. Dowgiewicz et al. (2011) and Trenholm et al. (2000) reported that total cell wall, hemicellulose, and lignocellulose were principal predictors of wear tolerance at the intra-specific level for creeping bentgrass (*Agrostis*), bermudagrass grass (*Cynodon dactylon* L.) and bermudagrass hybrids (*C. dactylon* L. x *C. transvaalensis*), respectively. However, due to the inconsistent effects of cell wall components on wear tolerance, Canaway (1978, 1981) proposed using only verdure biomass as a more reliable predictor for wear tolerance.

In study 3, multiple linear regression indicated that biomass of verdure and lignin contributed 30.3% of the total variation in tiller quality at the inter-specific level and 36.7% within hard fescue. Lignocellulose was the only significant variable in the models for Chewings fescue (R^2=23.8%) and strong creeping red fescue (33.3%) (Table 11). In study 4, only one model was significant at the 0.05 probability level; lignocellulose accounted for 23.3% of the total variation in Chewings fescue tiller quality (Table 12). Limited association of traffic tolerance with verdure parameters in study 4 was probably to the limited and greater variation (C.V.) of the fine fescue tiller-plot response to traffic (Table 1). It is also important to note that differences in wear or traffic tolerance among fine fescue tiller-plots were not as apparent as observed in turf plots. Turf plots permit better evaluation and greater segregation of wear tolerance among fine fescue species and cultivars, which also contributes to the development of more accurate regression models. Additionally, other mechanisms for wear tolerance, which were not considered as part of this study, may account for unexplained variation in wear tolerance observed in the fine fescue tiller-plot trials. Other factors including tiller and leaf angle, stem and leaf moisture, percent chlorophyll concentration and concentrations of K, Mn, and Mg have been reported to be related to wear tolerance (Dowgiewicz et al., 2011; Shearman and Beard, 1975a; Trenholm et al., 2000). Future studies may need to focus on the investigation of other potential characteristics to improve the screening efficacy of wear tolerant fine fescue tiller-plots

CONCLUSION

Considerable intra- and inter-specific variation in wear tolerance and the biomass and cell wall composition of verdure were present in fine fescue. A general pattern between wear tolerance and the biomass and cell wall constituents of the verdure were identified on inter-specific levels, and within Chewings and strong creeping red fescues, improved wear tolerance was associated with greater biomass and TCW and lignocellulose content as well as reduced lignin content. However, regression models to predict wear tolerance in hard fescues were not successful, which may due to limited genotypic and phenotypical diversity among the hard fescues tested in this study. The improvement in the wear tolerance through selecting for greater biomass and TCW and lignocellulose contents in verdure may be most promising for Chewings and strong creeping red fescues

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Table 7.1 Analysis of variance (ANOVA) and means of uniformity of turf canopy (UTC), fullness of turf cover (FTC) and tiller quality of three fine fescue species as response to wear and traffic

	-------- Study 1 [C] --------		-------- Study 2 --------		---- Study 3 ----	---- Study 4[¥] ----
	UTC[¶]	FTC[‡]	UTC	FTC	Tiller Quality[f]	Tiller Quality
Source of Variation						
Species	***	***	***	***	***	ns
Cultivars (Species)	*	**	**	***	***	***
Species	1 to 9	0 to 100	1 to 9	0 to 100	1 to 10	1 to 10
Chewings	3.8 b[†]	49 b	3.9 a	39 a	4.9 a	4.1
Hard	7.1 a	79 a	2.8 b	30 b	4.1 a	3.8
Strong Creeping	1.5 c	19 c	2.1 c	22 c	3.1 b	3.7

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
[§] ns, non-significant.
[C] Abrasive wear was applied with Rutgers Wear Simulator on Studies 1, 2, and 3
[¥] Traffic was applied with a traffic simulator imparts both wear and soil compaction on Study 4
[¶] Uniformity of turf canopy (UTC), 9= most uniform canopy, 1=least uniform canopy
[‡] Fullness of turf cover (FTC); 100% = full canopy, 0=no cover
[f] Tiller quality; 10 = no damage, 1= tiller death
[†] Numbers followed by the same letter(s) are not significantly different ($\alpha = 0.05$) for comparisons between species

Table 7.2 Analysis of variance (ANOVA) and means of verdure biomass of fine fescue samples collected from field plots (study 1 and 2) and tillers (study 3 and 4)

	Study 1	Study 2	Study 3	Study 4
Source of Variation				
Species	***	***	***	***
Cultivars (Species)	ns	ns	ns	***
Species	---------------------------- verdure biomass (kg/m^{-2}) ----------------------------			
Chewings	0.98 b[†]	0.45 b	0.56 b	0.49 a
Hard	1.44 a	0.53 a	0.59 a	0.35 b
Strong Creeping	0.88 c	0.41 c	0.49 c	0.29 c

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.0001$.
[§] ns, non-significant.
[†] Numbers followed by the same letter(s) are not significantly different ($\alpha = 0.05$) for comparisons between species

Table 7.3 Analysis of variance (ANOVA) and means of cell wall constituents of fine fescue samples collected from field plots (study 1 and 2) and tillers (study 3 and 4)

	Study 1					Study 2				
	TCW¶	Ligno-cellulose	Hemi-cellulose	Lignin	Cellulose	TCW	Ligno-cellulose	Hemi-cellulose	Lignin	Cellulose
Source of Variation										
Species	***	***	***	***	***	***	***	***	*	***
Cultivars (Species)	***	*	***	*	*	**	*	**	*	***
Species	%					%				
Chewings	61.4 a	31.7 b	29.8 a	7.8 b	21.8 a	62.3 a	28.8 a	33.5 a	5.8 ab	23.0 a
Hard	62.3 a	33.0 a	29.3 a	7.2 c	22.1 a	61.5 a	28.5 a	33.0 a	7.0 a	21.5 b
Strong Creeping	60.2 b	31.6 b	28.6 b	9.3 a	19.3 b	59.2 b	27.5 b	31.7 b	5.5 b	22.0 b

* Significant at p≤0.05.
** Significant at p≤0.01.
*** Significant at p≤0.0001.
§ ns, non-significant.
† Numbers followed by the same letter(s) are not significantly different (α = 0.05) for comparisons between species
¶ TCW=total cell wall content

Table 7.4 Analysis of variance (ANOVA) and means of cell wall constituents of fine fescue samples collected from field plots (study 1 and 2) and tillers (study 3 and 4)

	Study 3					Study 4				
	TCW	Ligno-cellulose	Hemi-cellulose	Lignin	Cellulose	TCW	Ligno-cellulose	Hemi-cellulose	Lignin	Cellulose
Source of Variation										
Species	***	***	***	***	***	***	***	ns	***	***
Cultivars (Species)	***	*	***	***	***	***	*	**	*	***
Species	------------------------- % -------------------------					------------------------- % -------------------------				
Chewings	64.6 a[†]	29.4 a	35.3 a	6.1 b	23.3 a	59.9 a	32.3 a	27.5 a	9.6 b	22.7 a
Hard	60.9 b	26.5 b	34.4 b	6.8 a	19.8 c	59.4 a	32.4 a	27.0 b	13.4 a	19.0 c
Strong Creeping	59.6 c	26.6 b	33.1 c	5.3 c	21.2 b	56.5 b	28.9 b	27.0	8.1 b	20.4 b

* Significant at $p \leq 0.05$.

** Significant at $p \leq 0.01$.

*** Significant at $p \leq 0.0001$.

[§] ns, non-significant.

[†] Numbers followed by the same letter(s) are not significantly different ($\alpha = 0.05$) for comparisons between species

[¶] TCW=total cell wall content

Table 7.5 Correlation coefficients among fine fescue traits and traffic tolerance parameters for study 1 (samples collected from Adelphia, NJ in October 2017)

	Correlation coefficients (significance level)					
Uniformity of Turf Cover	Verdure Biomass	TCW[¶]	Lignocellulose	Hemicellulose	Lignin	Cellulose
Chewings (n=18)	0.52[¶] p=0.027	0.26 p=0.291	-0.19 p=0.457	0.58 p=0.012	-0.13 p=0.619	0.52 p=0.028
Hard (n=26)	0.21 p=0.294	-0.27 p=0.189	0.04 p=0.853	-0.34 p=0.094	-0.19 p=0.364	-0.15 p=0.454
Strong Creeping (n=13)	0.67 p=0.012	0.22 p=0.462	-0.01 p=0.983	0.41 p=0.159	-0.53 p=0.065	0.59 p=0.032
Inter-species (n=57)	0.86 p<0.001	0.49 p<0.001	0.45 p<0.001	0.21 0.029	-0.59 p<0.001	0.54 p<0.001
Fullness of Turf Cover	Verdure Biomass	TCW	Lignocellulose	Hemicellulose	Lignin	Cellulose
Chewings (n=18)	0.58 p=0.011	0.37 p=0.133	-0.12 p=0.633	0.67 p=0.002	-0.10 p=0.703	0.57 p=0.014
Hard (n=26)	0.21 p=0.306	-0.39 p=0.048	-0.13 p=0.533	-0.35 p=0.080	-0.40 p=0.04.	-0.07 p=0.972
Strong Creeping (n=13)	0.69 p=0.009	0.22 p=0.478	0.01 p=0.976	0.38 p=0.206	-0.52 p=0.071	0.57 p=0.043
Inter-species (n=57)	0.84 p<0.001	0.51 p<0.001	0.41 p=0.002	0.29 p=0.029	-0.64 p<0.001	0.62 p<0.001

* Significant at p≤0.05.
** Significant at p≤0.01.
*** Significant at p≤0.0001.
[§] ns, non-significant.
[¶] TCW=total cell wall content
[¶] Correlation coefficients, + represents a positive effect, - represents a negative effect

Table 7.6 Correlation coefficients among fine fescue traits and traffic tolerance parameters for study 2 (sample collected from North Brunswick, NJ in July 2018)

	Correlation coefficients (significance level)					
Uniformity of Turf Cover	Verdure Biomass	TCW¶	Lignocellulose	Hemicellulose	Lignin	Cellulose
Chewings (n=16)	0.54 p=0.033	0.76 P<0.001	0.54 p=0.031	0.51 p=0.041	0.08 p=0.780	0.35 p=0.179
Hard (n=14)	0.09 p=0.763	0.40 p=0.153	0.01 p=0.971	0.47 p=0.087	-020 p=0.498	0.27 p=0.345
Strong Creeping (n=22)	-0.13 p=0.575	0.21 p=0.369	0.22 p=0.340	0.04 p=0.859	0.51 p=0.018	-0.40 p=0.071
Inter-species (n=52)	0.28 p=0.045	0.73 p<0.001	0.52 p<0.001	0.62 p<0.001	0.12 p=0.411	0.31 p=0.026
Fullness of Turf Cover	Verdure Biomass	TCW	Lignocellulose	Hemicellulose	Lignin	Cellulose
Chewings (n=16)	0.44 p=0.085	0.72 p=0.002	0.54 p=0.135	0.63 p=0.009	-0.18 p=0.499	0.49 p=0.054
Hard (n=14)	-0.22 p=0.445	0.44 p=0.119	-0.19 p=0.513	0.69 p=0.007	-0.169 p=0.563	0.08 p=0.780
Strong Creeping (n=22)	0.09 p=0.697	0.03 p=0.902	0.21 p=0.369	-0.16 p=0.491	0.38 p=0.086	-0.27 p=0.244
Inter-species (n=52)	0.24 p=0.08	0.72 p<0.001	0.45 p<0.001	0.68 p<0.001	0.07 p=0.063	0.30 p=0.030

* Significant at $p\leq0.05$.

** Significant at $p\leq0.01$.

*** Significant at $p\leq0.0001$.

§ ns, non-significant.

¶ TCW=total cell wall content

¶ Correlation coefficients, + represents a positive effect, - represents a negative effect

Table 7.7 Correlation coefficients among fine fescue traits and traffic tolerance parameters for study 3 (sample collected from North Brunswick, NJ in July 2018)

	Correlation coefficients (significance level)					
Tiller Quality	Verdure Biomass	TCW[¶]	Lignocellulose	Hemicellulose	Lignin	Cellulose
Chewings (n=61)	0.27[¶] p=0.033	0.48 p<0.001	0.49 P<0.001	0.44 p<0.001	0.31 p=0.014	0.01 p=0.927
Hard (n=61)	0.61 p<0.001	-0.03 p=0.826	-0.05 p=0.697	-0.01 p=0.920	-0.43 p<0.001	0.51 p<0.001
Strong Creeping (n=62)	0.46 p<0.001	0.54 p<0.001	0.58 p<0.001	0.38 p=0.003	-0.06 p=0.639	0.40 p=0.001
Inter-species (n=184)	0.55 p<0.001	0.20 p=0.006	0.12 p=0.106	0.26 p<0.001	0.39 p<0.001	-0.13 p=0.07

* Significant at p≤0.05.

** Significant at p≤0.01.

*** Significant at p≤0.0001.

[§] ns, non-significant.

[¶] TCW=total cell wall content

[¶] Correlation coefficients, + represents a positive effect, - represents a negative effect

Table 7.8 Correlation coefficients among fine fescue traits and traffic tolerance parameters for study 4 (sample collected from St. Paul, MN in August 2018)

	Correlation coefficients (significance level)					
Tiller Quality	Verdure Biomass	TCW¶	Lignocellulose	Hemicellulose	Lignin	Cellulose
Chewings (n=51)	0.36¶ p=0.093	0.47 p<0.001	0.48 p<0.001	-0.15 p=0.278	-0.34 p=0.014	0.34 p=0.015
Hard (n=39)	-0.07 p=0.673	0.14 p=0.411	0.12 p=0.466	0.01 p=0.995	-0.1 p=0.534	0.37 p=0.024
Strong Creeping (n=23)	-0.07 p=0.767	-0.16 p=0.474	-0.23 p=0.299	0.26 p=0.231	-0.25 p=0.242	0.18 p=0.416
Inter-species (n=113)	0.15 p=0.108	0.18 p=0.063	0.11 p=0.230	0.04 p=0.650	-0.06 p=0.510	0.30 p=0.001

* Significant at p≤0.05.
** Significant at p≤0.01.
*** Significant at p≤0.0001.
§ ns, non-significant.
¶ TCW=total cell wall content
¶ Correlation coefficients, + represents a positive effect, - represents a negative effect

Table 7.9 Multiple regression analysis (alpha=0.05) on uniformity of turf canopy (UTC), fullness of turf cover (FTC) in three fine fescue species using verdure biomass, TCW, lignocellulose and lignin for study 1(sample collected from Adelphia, NJ in October 2017)

	Predictors partial r^2 (parameter estimates)				Model r^2	
UTC	Verdure Biomass	TCW	Lignocellulose	Lignin	Final Model r^2	Full Model r^2
Chewings (n=18)	0.271[§] (+5.7)		0.219 (+0.5)		0.490	0.565
Hard (n=26)						
Strong Creeping (n=13)	0.451 (+3.2)			0.263 (-0.3)	0.713	0.716
Inter-species (n=57)	0.746 (+6.3)			0.094 (-0.6)	0.839	0.845
FTC	Verdure Biomass	TCW	Lignocellulose	Lignin	Final Model R^2	Full Model R^2
Chewings (n=18)	0.339 (+43.0)	0.123 (+4.3)			0.642	0.643
Hard (n=26)						
Strong Creeping (n=13)	0.481 (+47.6)			0.253 (-4.2)	0.734	0.739
Inter-species (n=57)	0.700 (+52.3)	0.013 (+2.6)		0.135 (-8.9)	0.849	0.850

[§] percent variations explained by the independent variables

[¶] parameter estimates of the independent variable, + represents positive effect, - represents a negative effect

Table 7.10 Multiple regression analysis (alpha=0.05) on uniformity of turf canopy in three fine fescue species using verdure biomass, TCW, lignocellulose and lignin for study 2 (sample collected from North Brunswick, NJ in July 2018)

	Predictors partial r^2 (parameter estimates)				Model r^2	
UTC	Verdure Biomass	TCW	Lignocellulose	Lignin	Final Model r^2	Full Model r^2
Chewings (n=16)	0.199 (+6.4)	0.574 (+0.4)			0.773	0.778
Hard (n=14)						ns
Strong Creeping (n=22)						ns
Inter-species (n=52)		0.530 (+0.4)			0.530	0.538
FTC	Verdure Biomass	TCW	Lignocellulose	Lignin	Final Model R^2	Full Model R^2
Chewings (n=16)	0.128 (+41.3)	0.523 (+3.1)			0.652	0.733
Hard (n=14)						ns
Strong Creeping (n=22)						ns
Inter-species (n=52)		0.521 (+3.8)			0.521	0.548

§ percent variations explained by the independent variables

¶ parameter estimates of the independent variable, + represents positive effect, - represents a negative effect

Table 7.11 Multiple regression analysis (alpha=0.05) on tiller quality in three fine fescue species using verdure biomass, TCW, lignocellulose and lignin for study 3(sample collected from North Brunswick, NJ in July 2018)

	Predictors partial r^2 (parameter estimates)				Model r^2	
Tiller Quality	Verdure Biomass	TCW	Lignocellulose	Lignin	Final Model R^2	Full Model R^2
Chewings (n=61)			0.238 (+2.1)		0.238	0.238
Hard (n=61)	0.367 (+9.9)				0.367	0.459
Strong Creeping (n=62)			0.333 (+1.6)		0.333	0.393
Inter-species (n=184)	0.303 (+9.1)			0.019 (+0.3)	0.321	0.330

§ percent variations explained by the independent variables

¶ parameter estimates of the independent variable, + represents positive effect, - represents a negative effect

Table 7.12 Multiple regression analysis (alpha=0.05) on tiller quality in three fine fescue species using verdure biomass, TCW, lignocellulose and lignin for study 4 (sample collected from St. Paul, MN in July 2018)

	Predictors partial r^2 (parameter estimates)				Model r^2	
Tiller Quality	Verdure Biomass	TCW	Lignocellulose	Lignin	Final Model R^2	Full Model R^2
Chewings (n=51)			0.233 (+0.2)		0.233	0.270
Hard (n=39)						
Strong Creeping (n=23)						
Inter-species (n=113)						

§ percent variations explained by the independent variables

¶ parameter estimates of the independent variable, + represents positive effect, - represents a negative effect

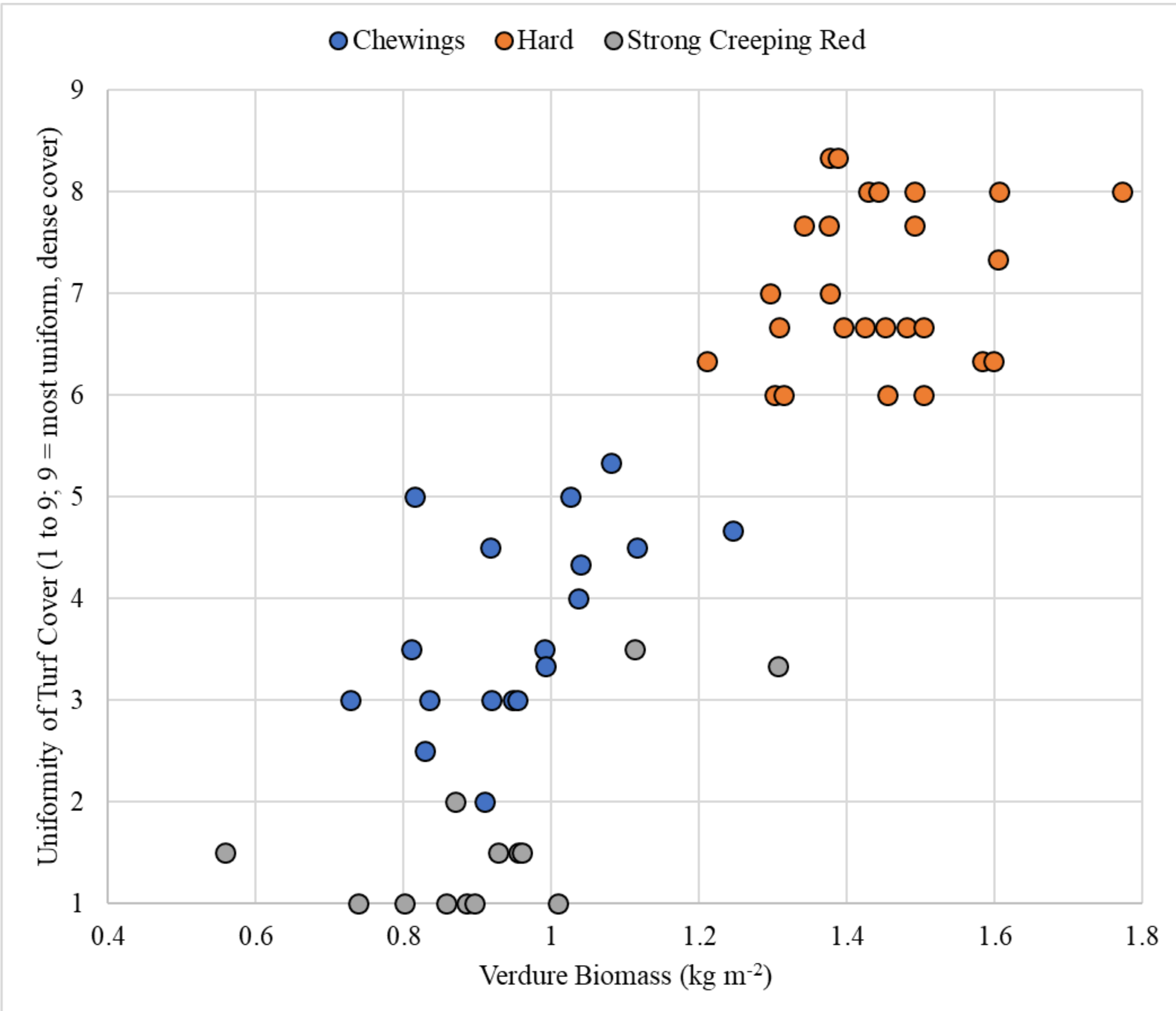

Figure 7.1 Scatter plot of uniformity of turf cover (Y-axis) and verdure biomass (X-axis) in three fine fescue species for study 1(sample collected from Adelphia, NJ in October 2017).

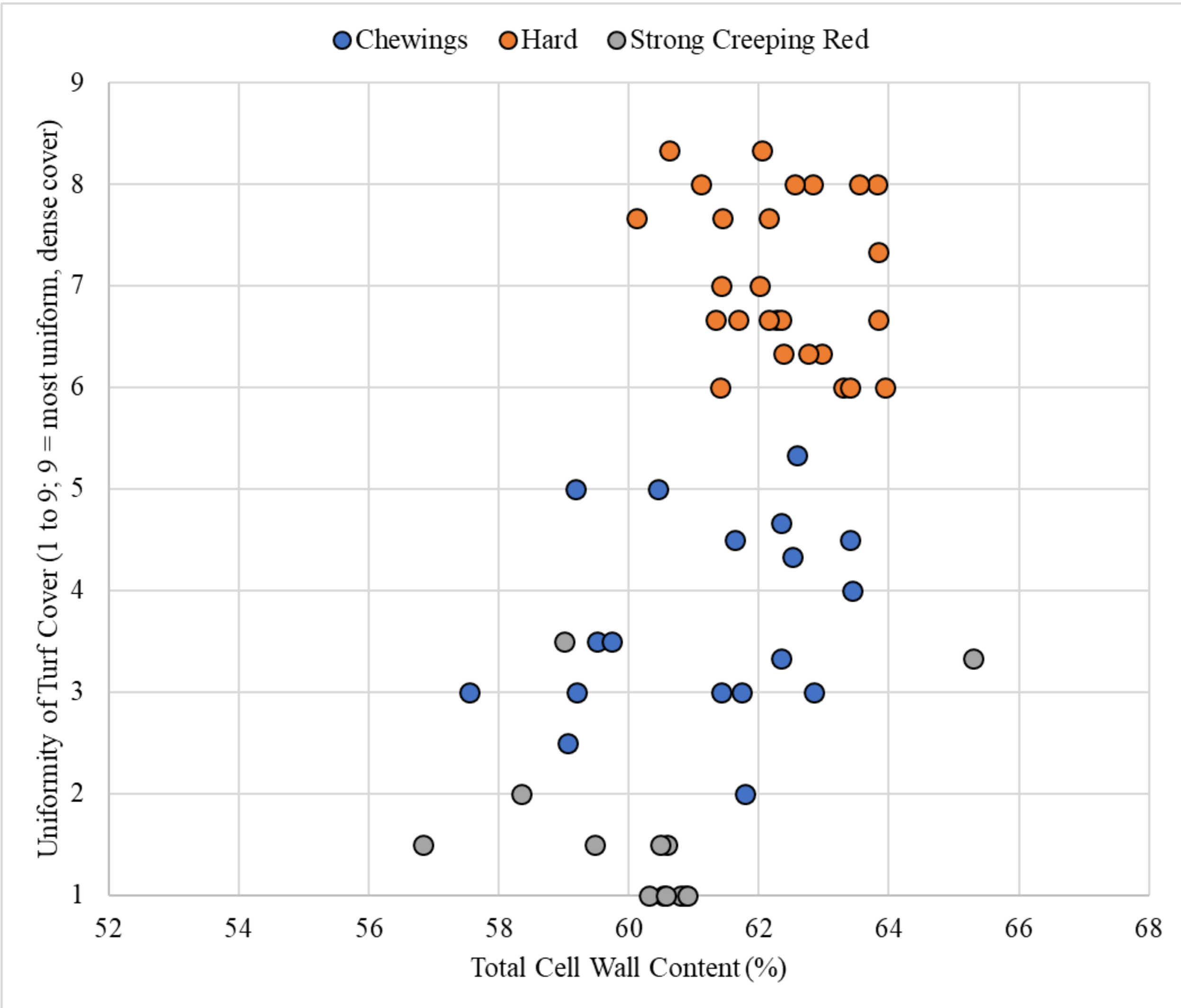

Figure 7.2 Scatter plot of uniformity of turf cover (Y-axis) and total cell wall concentration (X-axis) in three fine fescue species for study 1(sample collected from Adelphia, NJ in October 2017).

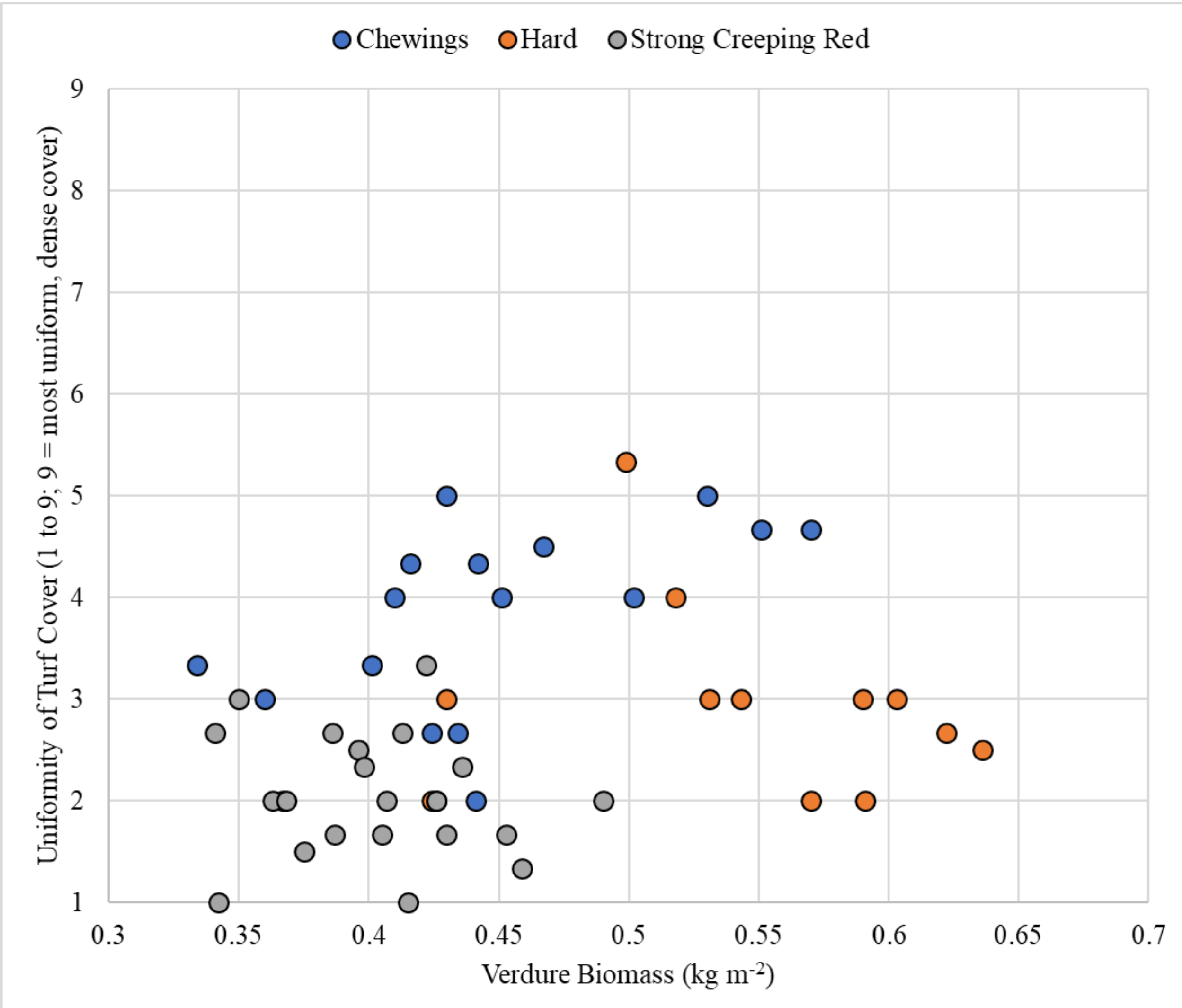

Figure 7.3 Scatter plot of uniformity of turf cover (Y-axis) and verdure biomass (X-axis) in three fine fescue species for study 2 (sample collected from North Brunswick, NJ in July 2018).

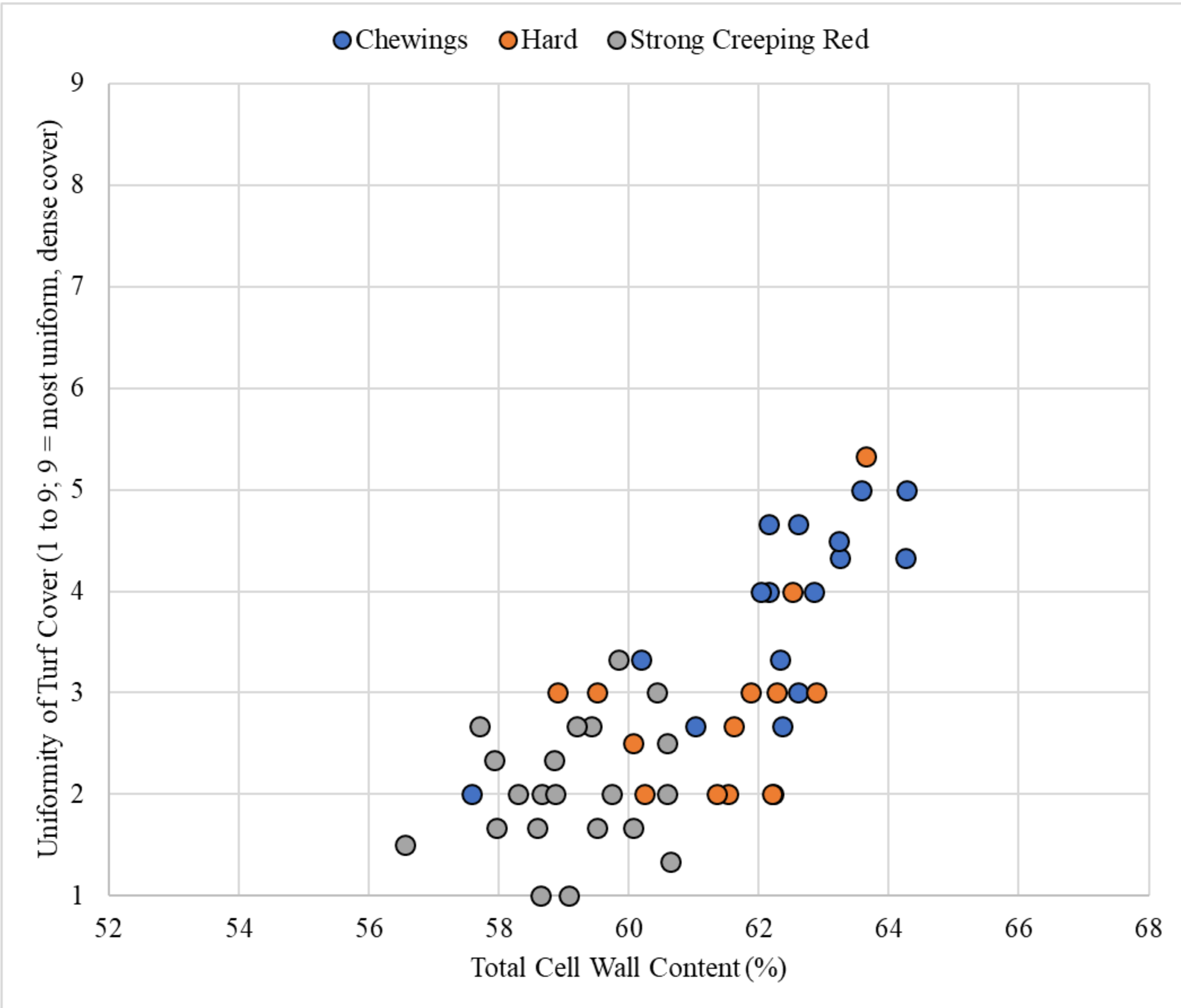

Figure 7.4 Scatter plot of uniformity of turf cover (Y-axis) and total cell wall concentration (X-axis) in three fine fescue species for study 2 (sample collected from North Brunswick, NJ in July 2018).

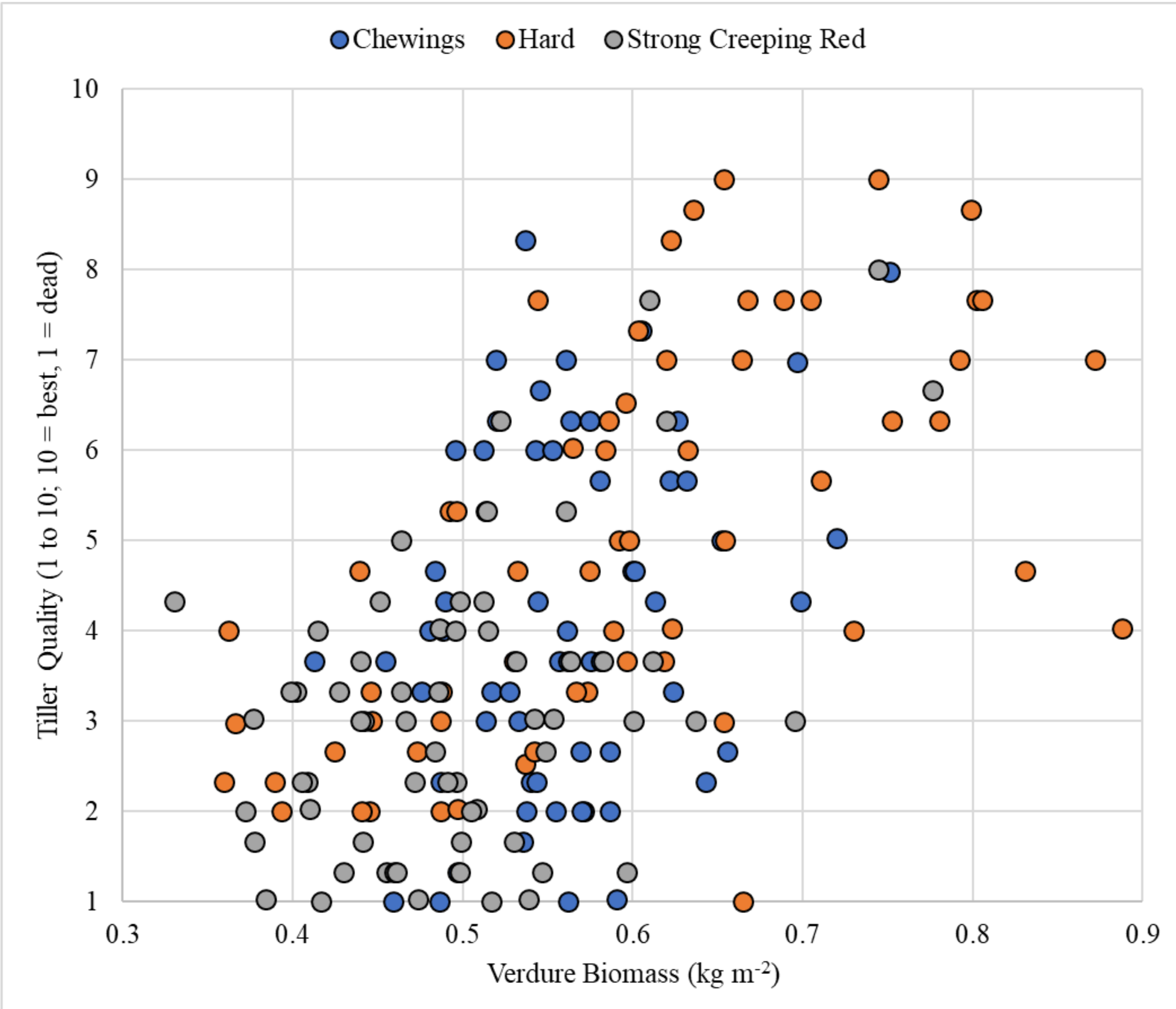

Figure 7.5 Scatter plot of tiller quality (Y-axis) and verdure biomass (X-axis) in three fine fescue species for study 3 (sample collected from North Brunswick, NJ in July 2018).

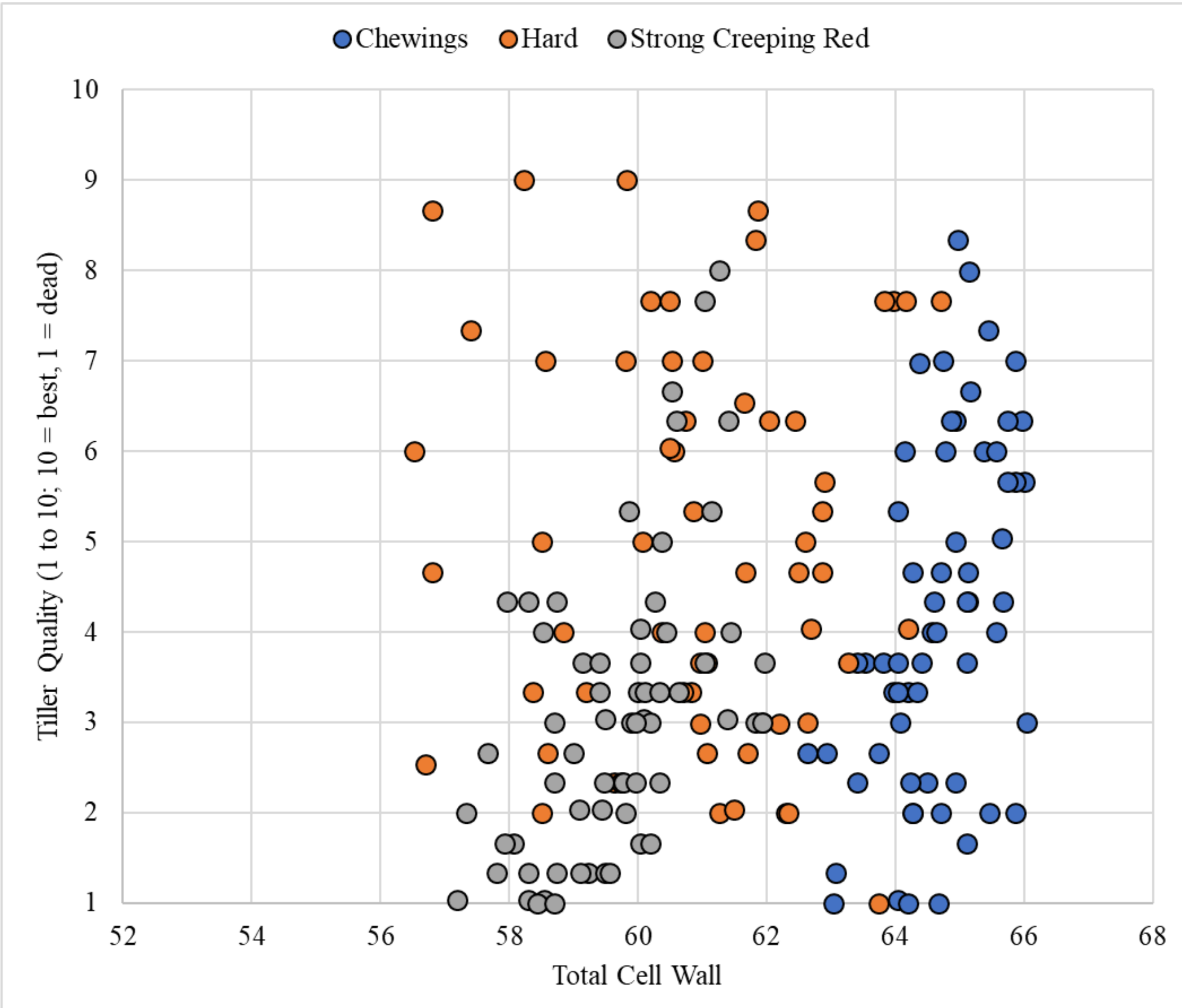

Figure 7.6 Scatter plot of tiller quality (Y-axis) and total cell wall concentration (X-axis) in three fine fescue species for study 3 (sample collected from North Brunswick, NJ in July 2018).

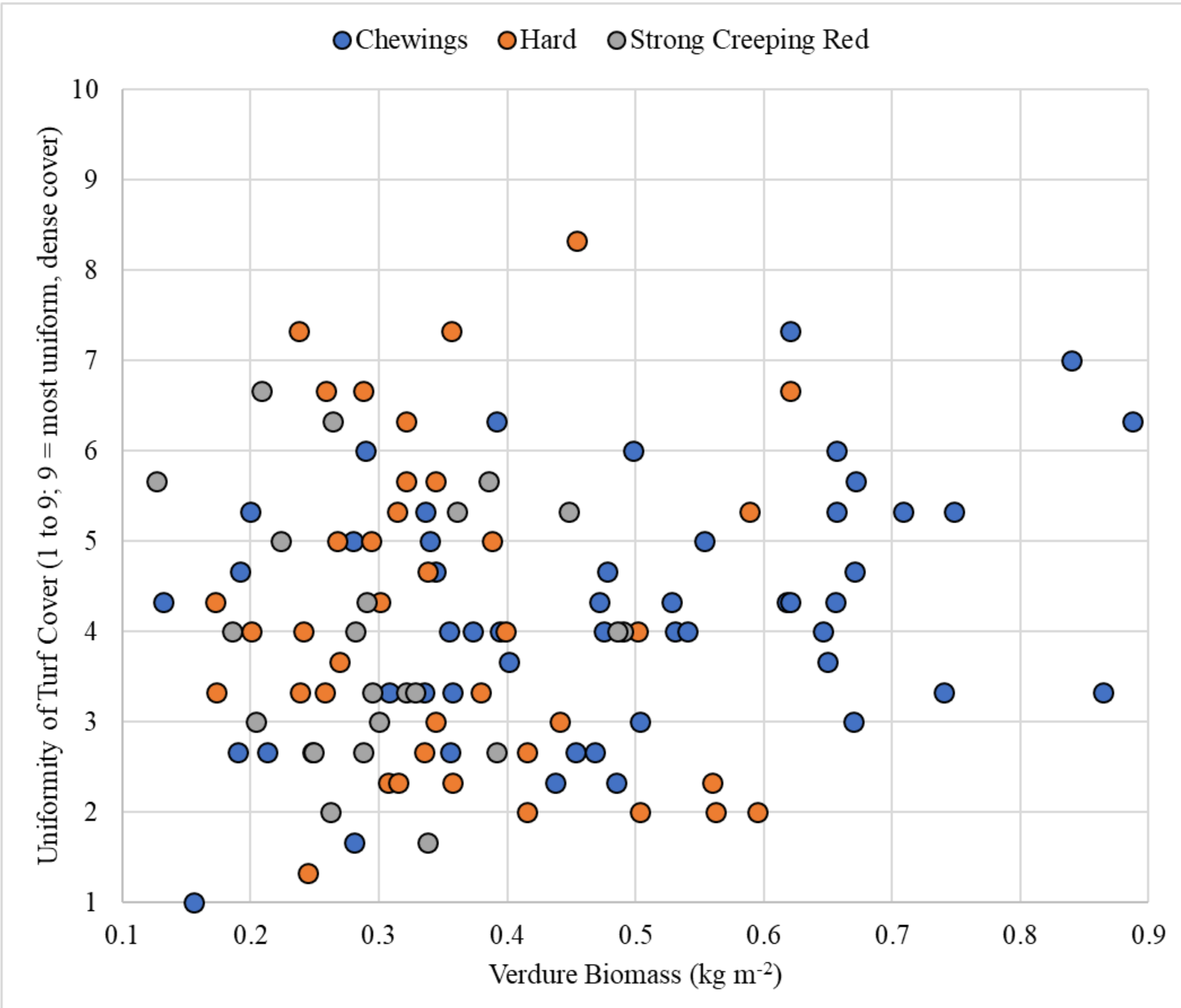

Figure 7.7 Scatter plot of tiller quality (Y-axis) and verdure biomass (X-axis) in three fine fescue species for study 4 (sample collected from St. Paul, MN in July 2018)

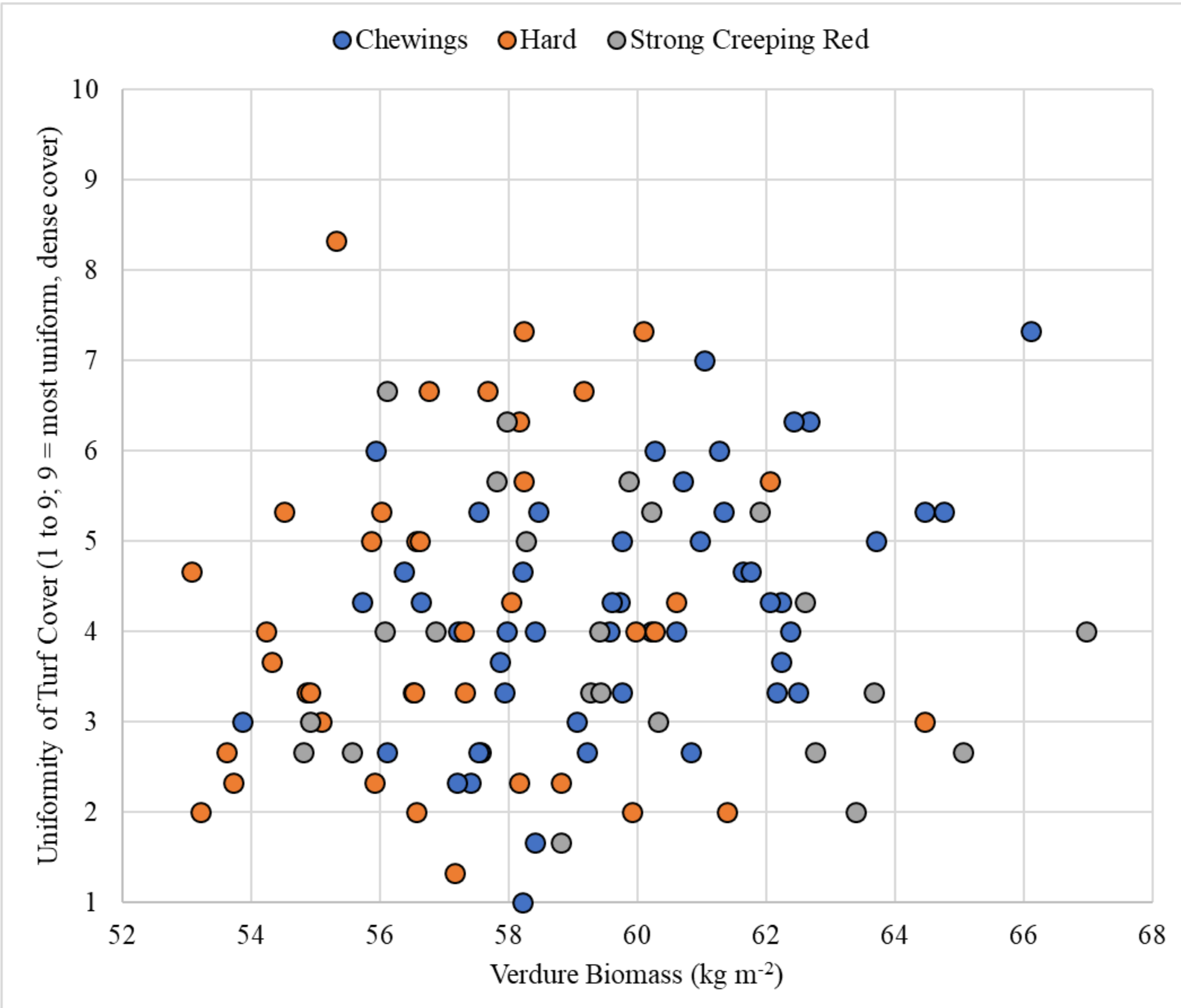

Figure 7.8 Scatter plot of tiller quality (Y-axis) and total cell wall concentration (X-axis) in three fine fescue species for study 4 (sample collected from St. Paul, MN in July 2018)

APPENDIX A

Table A.1 List of Chewings fescue used for near-infrared reflectance spectroscopy (NIRS) model development to predict total cell wall content, lignocellulose, hemicellulose, lignin, and cellulose.

No.	Sample ID	Location	Harvest Time (Year-Month)	Type	Mowing Height
1	AdelphiaFF5Oct2017Plot002_MEW2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
2	AdelphiaFF5Oct2017Plot003_MEW3_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
3	AdelphiaFF5Oct2017Plot004_7W1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
4	AdelphiaFF5Oct2017Plot005_7W2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
5	AdelphiaFF5Oct2017Plot006_7W3_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
6	AdelphiaFF5Oct2017Plot007_7W4_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
7	AdelphiaFF5Oct2017Plot008_PSG_50C3	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
8	AdelphiaFF5Oct2017Plot009_SR5_130	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
9	AdelphiaFF5Oct2017Plot013_PPG_FRC_113	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
10	AdelphiaFF5Oct2017Plot018_RADAR	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
11	AdelphiaFF5Oct2017Plot112_7W2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
12	AdelphiaFF5Oct2017Plot123_PPG_FRC_115	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
13	AdelphiaFF5Oct2017Plot129_COMPASS	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
14	AdelphiaFF5Oct2017Plot132_PPG_FRC_107	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
15	AdelphiaFF5Oct2017Plot137_4SHR_CH	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
16	AdelphiaFF5Oct2017Plot138_SR5130	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
17	AdelphiaFF5Oct2017Plot140_PSG_50C3	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
18	AdelphiaFF5Oct2017Plot146_MEW2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm

19	AdelphiaFF5Oct2017Plot158_MEW1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
20	AdelphiaFF5Oct2017Plot171_WINDWARD	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
21	AdelphiaFF5Oct2017Plot173_7W1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
22	AdelphiaFF5Oct2017Plot185_ACHY	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
23	AdelphiaFF5Oct2017Plot189_RADAR	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
24	AdelphiaFF5Oct2017Plot203_AMBROSE	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
25	AdelphiaFF5Oct2017Plot204_08_5FCE+	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
26	AdelphiaFF5Oct2017Plot205_MISER	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
27	AdelphiaFF5Oct2017Plot210_MEW3_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
28	AdelphiaFF5Oct2017Plot213_PPG_FRC_114	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
29	AdelphiaFF5Oct2017Plot215_FAIRMONT	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
30	AdelphiaFF5Oct2017Plot219_PPG_FRC_103	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
31	AdelphiaFF5Oct2017Plot224_7W2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
32	AdelphiaFF5Oct2017Plot228_AMBROSE	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
33	AdelphiaFF5Oct2017Plot229_7W3_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
34	AdelphiaFF5Oct2017Plot231_4CHY	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
35	AdelphiaFF5Oct2017Plot233_PSG_50C3	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
36	AdelphiaFF5Oct2017Plot238_MEW1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
37	AdelphiaFF5Oct2017Plot241_PPG_FRC_114	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
38	AdelphiaFF5Oct2017Plot244_7W1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
39	AdelphiaFF5Oct2017Plot255_MEW2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
40	AdelphiaFF5Oct2017Plot257_PPG_FRC_107	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
41	AdelphiaFF5Oct2017Plot273_WINDWARD	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
42	AdelphiaFF5Oct2017Plot277_PPG_FRC_103	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm

43	AdelphiaFF5Oct2017Plot278_FAIRMONT	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
44	AdelphiaFF5Oct2017Plot284_7W14_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
45	AdelphiaFF5Oct2017Plot296_4SHR_CH	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
46	AdelphiaFF5Oct2017Plot302_RADAR	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
47	AdelphiaFF5Oct2017Plot313_SHADOW_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
48	AdelphiaFF5Oct2017Plot316_PPG_FRC_113	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
49	AdelphiaFF5Oct2017Plot322_PPG_FRC_115	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
50	AdelphiaFF5Oct2017Plot330_FT6_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
51	F21TrafficSep2017P003_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
52	F21TrafficSep2017P004_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
53	F21TrafficSep2017P012_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
54	F21TrafficSep2017P016_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
55	F21TrafficSep2017P027_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
56	F21TrafficSep2017P030_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
57	F21TrafficSep2017P039_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
58	F21TrafficSep2017P040_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
59	F21TrafficSep2017P044_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
60	F21TrafficSep2017P050_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
61	F21TrafficSep2017P052_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
62	F21TrafficSep2017P059_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
63	F21TrafficSep2017P067_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
64	F21TrafficSep2017P068_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
65	F21TrafficSep2017P080_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
66	F21TrafficSep2017P089_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm

67	F21TrafficSep2017P090_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
68	F21TrafficSep2017P095_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
69	F21TrafficSep2017P098_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
70	F21TrafficSep2017P105_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
71	F21TrafficSep2017P107_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
72	F21TrafficSep2017P113_RADAR	North Brunswick, NJ	Sept. 2017	Turf plot	6.4 cm
73	F21TrafficSep2017P117_CULUMBRA_II	North Brunswick, NJ	Sept. 2017	Tiller	6.4 cm
74	MN_C_B2C18R1_3W2_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
75	MN_C_B2C18R3_3W2_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
76	MN_C_B2C18R4_3W1_36	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
77	MN_C_B2C19R1_A11_70_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
78	MN_C_B2C19R4_3W3_21	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
79	MN_C_B2C19R5_A11_50_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
80	MN_C_B2C19R7_A11_439_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
81	MN_C_B2C19R8_3W1_50	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
82	MN_C_B2C20R1_A11_74_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
83	MN_C_B2C20R3_3W3_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
84	MN_C_B2C20R5_A11_74_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
85	MN_C_B2C21R5_A11_74_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
86	MN_C_B2C21R6_3W1_38	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
87	MN_C_B2C22R1_3W2_16	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
88	MN_C_B2C22R2_A11_437_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
89	MN_C_B2C22R5_A11_439_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
90	MN_C_B2C22R7_A11_50_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm

91	MN_C_B2C22R8_3W1_15	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
92	MN_C_B2C23R2_A11_70_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
93	MN_C_B2C24R3_3W1_35	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
94	MN_C_B2C24R6_3W1_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
95	MN_C_B2C24R9_3W1_28	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
96	MN_C_B2C25R1_3W1_42	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
97	MN_C_B2C25R8_A11_437_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
98	MN_C_B2C26R1_3W1_37	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
99	MN_C_B2C26R3_3W3_31	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
100	MN_C_B2C27R2_3W2_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
101	MN_C_B2C27R3_3W1_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
102	MN_C_B2C27R8_3W1_19	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
103	MN_C_B2C28R2_3W1_48	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
104	MN_C_B2C28R4_A11_50_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
105	MN_C_B2C28R6_A11_48_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
106	MN_C_B2C28R8_A11_74_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
107	MN_C_B2C28R9_3W3_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
108	MN_C_B2C29R1_3W1_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
109	MN_C_B2C29R8_A11_440_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
110	MN_C_B2C30R1_A11_48_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
111	MN_C_B2C30R2_A11_50_9	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
112	MN_C_B2C30R8_3W2_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
113	MN_C_B2C30R9_3W2_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
114	MN_C_B2C31R6_3W3_28	St. Paul, MN	Aug. 2018	Tiller	7.6 cm

115	MN_C_B2C31R8_A11_439_10	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
116	MN_C_B2C32R1_A11_438_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
117	MN_C_B2C32R5_A11_51_10	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
118	MN_C_B2C32R6_3W1_26	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
119	MN_C_B2C32R7_3W2_18	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
120	MN_C_B2C32R8_A11_439_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
121	MN_C_B2C33R2_A11_50_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
122	MN_C_B2C33R6_3W3_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
123	MN_C_B2C35R1_A11_50_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
124	MN_C_B2C35R3_A11_51_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
125	MN_C_B2C35R4_A11_51_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
126	NJ_C_R3R68P04_3W1_38	North Brunswick, NJ	July 2018	Tiller	7.6 cm
127	NJ_C_R3R68P07_3W1_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
128	NJ_C_R3R68P08_3W2_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
129	NJ_C_R3R68P09_3W3_22	North Brunswick, NJ	July 2018	Tiller	7.6 cm
130	NJ_C_R3R69P04_3W3_24	North Brunswick, NJ	July 2018	Tiller	7.6 cm
131	NJ_C_R3R69P05_3W2_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
132	NJ_C_R3R69P06_A11_50_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
133	NJ_C_R3R69P07_A11_74_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
134	NJ_C_R3R69P09_A11_70_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
135	NJ_C_R3R69P10_A11_48_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
136	NJ_C_R3R69P11_A11_74_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
137	NJ_C_R3R70P01_3W1_19	North Brunswick, NJ	July 2018	Tiller	7.6 cm
138	NJ_C_R3R70P02_3W3_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm

139	NJ_C_R3R70P04_A11_50_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
140	NJ_C_R3R70P05_3W2_116	North Brunswick, NJ	July 2018	Tiller	7.6 cm
141	NJ_C_R3R70P12_A11_438_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
142	NJ_C_R3R71P03_3W1_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
143	NJ_C_R3R71P04_3W1_48	North Brunswick, NJ	July 2018	Tiller	7.6 cm
144	NJ_C_R3R71P05_A11_440_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
145	NJ_C_R3R71P11_3W3_28	North Brunswick, NJ	July 2018	Tiller	7.6 cm
146	NJ_C_R3R72P03_A11_48_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
147	NJ_C_R3R72P10_A11_50_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
148	NJ_C_R3R73P01_A11_51_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
149	NJ_C_R3R73P02_A11_51_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
150	NJ_C_R3R73P05_A11_439_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
151	NJ_C_R3R73P12_A11_74_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
152	NJ_C_R3R74P01_3W1_36	North Brunswick, NJ	July 2018	Tiller	7.6 cm
153	NJ_C_R3R74P03_A11_74_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
154	NJ_C_R3R74P08_A11_50_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
155	NJ_C_R3R74P11_3W3_31	North Brunswick, NJ	July 2018	Tiller	7.6 cm
156	NJ_C_R3R75P05_3W2_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
157	NJ_C_R3R75P06_3W1_43	North Brunswick, NJ	July 2018	Tiller	7.6 cm
158	NJ_C_R3R75P07_A11_437_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
159	NJ_C_R3R75P10_A11_50_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
160	NJ_C_R3R76P03_3W1_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
161	NJ_C_R3R76P04_3W3_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
162	NJ_C_R3R76P06_A11_48_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm

163	NJ_C_R3R76P07_3W2_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
164	NJ_C_R3R76P08_3W2_20	North Brunswick, NJ	July 2018	Tiller	7.6 cm
165	NJ_C_R3R76P09_A11_48_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
166	NJ_C_R3R76P10_A11_74_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
167	NJ_C_R3R76P11_3W2_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
168	NJ_C_R3R77P01_3W1_26	North Brunswick, NJ	July 2018	Tiller	7.6 cm
169	NJ_C_R3R77P02_3W1_28	North Brunswick, NJ	July 2018	Tiller	7.6 cm
170	NJ_C_R3R77P08_A11_51_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
171	NJ_C_R3R77P09_A11_50_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
172	NJ_C_R3R77P10_3W1_50	North Brunswick, NJ	July 2018	Tiller	7.6 cm
173	NJ_C_R3R77P11_A11_539_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
174	NJ_C_R3R78P02_A11_51_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
175	NJ_C_R3R78P03_A11_440_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
176	NJ_C_R3R78P05_3W1_31	North Brunswick, NJ	July 2018	Tiller	7.6 cm
177	NJ_C_R3R78P11_A11_437_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
178	NJ_C_R3R78P12_3W3_21	North Brunswick, NJ	July 2018	Tiller	7.6 cm
179	NJ_C_R3R79P07_3W2_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
180	NJ_C_R3R79P09_A11_440_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
181	NJ_C_R3R79P11_A11_50_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
182	NJ_C_R3R79P12_A11_439_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
183	NJ_C_R3R80P02_3W3_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
184	NJ_C_R3R80P03_A11_438_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
185	NJ_C_R3R80P04_A11_70_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
186	NJ_C_R3R80P06_3W2_18	North Brunswick, NJ	July 2018	Tiller	7.6 cm

187	NJ_C_R3R80P07_3W1_37	North Brunswick, NJ	July 2018	Tiller	7.6 cm
188	NJ_C_R3R80P09_A11_438_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
189	F21A3(ck)071718p004_RUSHMORE	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
190	F21A3(ck)071718p005_SURVIVOR	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
191	F21A3(ck)071718p007_FFR_102	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
192	F21A3(ck)071718p016_RADAR	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
193	F21A3(ck)071718p018_7W3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
194	F21A3(ck)071718p019_SHADOW_II	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
195	F21A3(ck)071718p023_OC1	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
196	F21A3(ck)071718p026_FAIRMONT	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
197	F21A3(ck)071718p034_S572_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
198	F21A3(ck)071718p038_AMBASSADOR	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
199	F21A3(ck)071718p045_AMBROSE	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
200	F21A3(ck)071718p049_LONGFELLOW_3	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
201	F21A3(ck)071718p050_CULUMBRA_II	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
202	F21A3(ck)071718p053_KOKET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
203	F21A3(ck)071718p059_LONGFELLOW_II	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
204	F21A3(ck)071718p060_7W2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
205	F21A3(ck)071718p062_C572_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
206	F21A3(ck)071718p068_LONGFELLOW_3	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
207	F21A3(ck)071718p069_RUSHMORE	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
208	F21A3(ck)071718p071_KOKET	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
209	F21A3(ck)071718p072_CULUMBRA_II	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
210	F21A3(ck)071718p075_AMBROSE	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm

211	F21A3(ck)071718p078_SHADOW_II	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
212	F21A3(ck)071718p080_RADAR	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
213	F21A3(ck)071718p081__FAIRMONT	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
214	F21A3(ck)071718p093_7W2_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
215	F21A3(ck)071718p094_7W3_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
216	F21A3(ck)071718p096_C571_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
217	F21A3(ck)071718p106_C572_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
218	F21A3(ck)071718p112_LONGFELLOW_II	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
219	F21A3(ck)071718p119_FFR_102	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
220	F21A3(ck)071718p123_J_5	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
221	F21A3(ck)071718p125_SURVIVOR	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
222	F21A3(ck)071718p130_OC1	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
223	F21A3(ck)071718p132_AMBASSADOR	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
224	F21A3(ck)071718p133_AMBROSE	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
225	F21A3(ck)071718p135_7W3_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
226	F21A3(ck)071718p138_SHADOW_II	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
227	F21A3(ck)071718p139_FAIRMONT	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
228	F21A3(ck)071718p140_LONGFELLOW_II	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
229	F21A3(ck)071718p143_OC1	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
230	F21A3(ck)071718p144_FFR_102	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
231	F21A3(ck)071718p146_7W2_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
232	F21A3(ck)071718p150_SURVIVOR	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
233	F21A3(ck)071718p153_J_5	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
234	F21A3(ck)071718p155_LONGFELLOW_3	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm

235	F21A3(ck)071718p156_KOKET	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
236	F21A3(ck)071718p171_AMBASSADOR	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
237	F21A3(ck)071718p172_RADAR	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
238	F21A3(ck)071718p174_CULUMBRA_II	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
239	F21A3(ck)071718p177_C572_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
240	F21A3(ck)071718p182_C571_COMP	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm
241	F21A3(ck)071718p195_RUSHMORE	North Brunswick, NJ	Aug. 2018	Turf plot	6.4 cm

Table A.2 List of hard fescue used for near-infrared reflectance spectroscopy (NIRS) model development to predict total cell wall content, lignocellulose, hemicellulose, lignin, and cellulose.

No.	Sample ID	Location	Harvest Time	Type	Mowing Height
1	AdelphiaFF5Oct2017Plot086_MEH2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
2	AdelphiaFF5Oct2017Plot087_TE1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
3	AdelphiaFF5Oct2017Plot088_TE2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
4	AdelphiaFF5Oct2017Plot089_BM2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
5	AdelphiaFF5Oct2017Plot090_H571_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
6	AdelphiaFF5Oct2017Plot091_H573_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
7	AdelphiaFF5Oct2017Plot092_H575_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
8	AdelphiaFF5Oct2017Plot093_7H1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
9	AdelphiaFF5Oct2017Plot094_7H2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
10	AdelphiaFF5Oct2017Plot095_7H3_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
11	AdelphiaFF5Oct2017Plot096_7H4_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
12	AdelphiaFF5Oct2017Plot097_7H4	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
13	AdelphiaFF5Oct2017Plot098_7HF	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
14	AdelphiaFF5Oct2017Plot099_7H6_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
15	AdelphiaFF5Oct2017Plot100_PPG_106	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
16	AdelphiaFF5Oct2017Plot101_PPG_107	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
17	AdelphiaFF5Oct2017Plot102_PPG_108	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
18	AdelphiaFF5Oct2017Plot103_BEACON	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
19	AdelphiaFF5Oct2017Plot104_RELIANT_IV	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
20	AdelphiaFF5Oct2017Plot105_PREDATOR	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
21	AdelphiaFF5Oct2017Plot106_OXFORD	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm

22	AdelphiaFF5Oct2017Plot107_4BND	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
23	AdelphiaFF5Oct2017Plot108_7H2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
24	AdelphiaFF5Oct2017Plot109_PSG_TH3	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
25	AdelphiaFF5Oct2017Plot110_SPARTAN_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
26	AdelphiaFF5Oct2017Plot111_7H1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
27	AdelphiaFF5Oct2017Plot119_TE2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
28	AdelphiaFF5Oct2017Plot120_PPG_FL_108	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
29	AdelphiaFF5Oct2017Plot133_PPG_FL_107	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
30	AdelphiaFF5Oct2017Plot134_SPARTAN_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
31	AdelphiaFF5Oct2017Plot141_7H4	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
32	AdelphiaFF5Oct2017Plot143_H573_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
33	AdelphiaFF5Oct2017Plot144_OXFORD	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
34	AdelphiaFF5Oct2017Plot148_TE1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
35	AdelphiaFF5Oct2017Plot153_MEH2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
36	AdelphiaFF5Oct2017Plot154_7H6_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
37	AdelphiaFF5Oct2017Plot156_7H3_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
38	AdelphiaFF5Oct2017Plot160_RELIANT_IV	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
39	AdelphiaFF5Oct2017Plot161_7H4_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
40	AdelphiaFF5Oct2017Plot176_BEACON	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
41	AdelphiaFF5Oct2017Plot181_7HF	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
42	AdelphiaFF5Oct2017Plot187_PPG_FL-106	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
43	AdelphiaFF5Oct2017Plot190_MEH1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
44	AdelphiaFF5Oct2017Plot194_PSG_TH3	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
45	AdelphiaFF5Oct2017Plot195_7H2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm

46	AdelphiaFF5Oct2017Plot197_4BND	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
47	AdelphiaFF5Oct2017Plot198_7H2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
48	AdelphiaFF5Oct2017Plot199_BM2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
49	AdelphiaFF5Oct2017Plot209_PREDATOR	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
50	AdelphiaFF5Oct2017Plot218_H571_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
51	AdelphiaFF5Oct2017Plot2397H2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
52	AdelphiaFF5Oct2017Plot240_7H1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
53	AdelphiaFF5Oct2017Plot247_OXFORD	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
54	AdelphiaFF5Oct2017Plot251_PPG_FL_106	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
55	AdelphiaFF5Oct2017Plot252_7HF	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
56	AdelphiaFF5Oct2017Plot256_H571_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
57	AdelphiaFF5Oct2017Plot258_SPARTAN_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
58	AdelphiaFF5Oct2017Plot260_7H6_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
59	AdelphiaFF5Oct2017Plot267_BEACON	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
60	AdelphiaFF5Oct2017Plot269_H575_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
61	AdelphiaFF5Oct2017Plot270_BM2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
62	AdelphiaFF5Oct2017Plot271_RELIANT_IV	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
63	AdelphiaFF5Oct2017Plot272_4BND	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
64	AdelphiaFF5Oct2017Plot279_PPG_FL_107	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
65	AdelphiaFF5Oct2017Plot280_7H4_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
66	AdelphiaFF5Oct2017Plot281_7H4	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
67	AdelphiaFF5Oct2017Plot289_7H2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
68	AdelphiaFF5Oct2017Plot290_MEH1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
69	AdelphiaFF5Oct2017Plot291_PREDATOR	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm

70	AdelphiaFF5Oct2017Plot294_TE2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
71	AdelphiaFF5Oct2017Plot300_H573_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
72	AdelphiaFF5Oct2017Plot312_PSG_TH3	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
73	AdelphiaFF5Oct2017Plot315_TE1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
74	AdelphiaFF5Oct2017Plot321_PPG_FL_108	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
75	AdelphiaFF5Oct2017Plot323_7H3_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
76	AdelphiaFF5Oct2017Plot328_MEH2_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
77	F21TrafficSep2017P002_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
78	F21TrafficSep2017P010_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
79	F21TrafficSep2017P014_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
80	F21TrafficSep2017P020_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
81	F21TrafficSep2017P025_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
82	F21TrafficSep2017P028_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
83	F21TrafficSep2017P031_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
84	F21TrafficSep2017P033_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
85	F21TrafficSep2017P043_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
86	F21TrafficSep2017P048_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
87	F21TrafficSep2017P051_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
88	F21TrafficSep2017P056_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
89	F21TrafficSep2017P065_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
90	F21TrafficSep2017P066_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
91	F21TrafficSep2017P071_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
92	F21TrafficSep2017P072_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
93	F21TrafficSep2017P081_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

94	F21TrafficSep2017P082_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
95	F21TrafficSep2017P096_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
96	F21TrafficSep2017P106_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
97	F21TrafficSep2017P108_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
98	F21TrafficSep2017P114_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
99	MN_Hard_B1C00R1_DA4_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
100	MN_Hard_B1C00R6_DA3_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
101	MN_Hard_B1C01R5_A11_86_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
102	MN_Hard_B1C02R1_A11_86_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
103	MN_Hard_B1C02R3_A11_88_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
104	MN_Hard_B1C02R4_A11_88_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
105	MN_Hard_B1C02R5_A11_88_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
106	MN_Hard_B1C02R7_A11_88_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
107	MN_Hard_B1C03R1_A11_88_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
108	MN_Hard_B1C03R5_A11_88_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
109	MN_Hard_B1C03R6_A11_94_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
110	MN_Hard_B1C03R7_A11_94_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
111	MN_Hard_B1C03R8_A11_94_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
112	MN_Hard_B1C04R1_A11_94_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
113	MN_Hard_B1C04R2_A11_94_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
114	MN_Hard_B1C04R3_A11_94_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
115	MN_Hard_B1C04R4_A11_94_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
116	MN_Hard_B1C04R5_A11_94_9	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
117	MN_Hard_B1C04R7_A11_94_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm

118	MN_Hard_B1C05R1_A11_258_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
119	MN_Hard_B1C05R2_A11-258-3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
120	MN_Hard_B1C05R3_A11-258-4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
121	MN_Hard_B1C05R4_A11-258-5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
122	MN_Hard_B1C05R8_A11-258-9	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
123	MN_Hard_B1C06R1_A11-258-11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
124	MN_Hard_B1C06R2_A11-258-12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
125	MN_Hard_B1C06R3_A11-259-1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
126	MN_Hard_B1C06R4_A11-259-2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
127	MN_Hard_B1C06R6_A11-259-4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
128	MN_Hard_B1C07R1_A11-259-8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
129	MN_Hard_B1C07R2_A11-259-9	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
130	MN_Hard_B1C08R1_DA4_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
131	MN_Hard_B1C08R2_DA4_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
132	MN_Hard_B1C09R1_DA4_18	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
133	MN_Hard_B1C09R2_DA4_19	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
134	MN_Hard_B1C10R2_DA4_31	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
135	MN_Hard_B1C10R7_DA3_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
136	MN_Hard_B1C10R8_DA3_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
137	MN_Hard_B1C10R9_DA3_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
138	MN_Hard_B1C11R1_DA3_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
139	MN_Hard_B1C11R3_DA3_9	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
140	MN_Hard_B1C11R5_DA3_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
141	MN_Hard_B1C11R7_DA3_13	St. Paul, MN	Aug. 2018	Tiller	7.6 cm

142	MN_Hard_B1C12R1_DA3_19	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
143	MN_Hard_B1C12R2_DA3_26	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
144	MN_Hard_B1C12R4_A11_90_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
145	MN_Hard_B1C12R5_A11_90_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
146	MN_Hard_B1C12R7_A11_90_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
147	MN_Hard_B1C13R1_A11_90_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
148	MN_Hard_B1C13R2_A11_90_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
149	MN_Hard_B1C13R3_A11_90_9	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
150	MN_Hard_B1C13R5_A11_90_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
151	MN_Hard_B1C13R6_A11_90_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
152	MN_Hard_B1C14R1_A11_246_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
153	MN_Hard_B1C14R2_A11_246_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
154	MN_Hard_B1C14R3_A11_246_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
155	MN_Hard_B1C15R1_A11_93_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
156	MN_Hard_B1C15R4_A11_93_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
157	MN_Hard_B1C15R6_A11_93_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
158	MN_Hard_B1C16R1_A11_93_10	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
159	MN_Hard_B1C16R4_A11_92_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
160	MN_Hard_B1C17R5_A11_92_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
161	MN_Hard_B1C17R6_A11_92_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
162	NJ_H_R2R42P03_DA3_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
163	NJ_H_R2R42P04_DA4_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
164	NJ_H_R2R42P06_DA4_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
165	NJ_H_R2R42P09_A11_86_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm

166	NJ_H_R2R42P10_A11_90_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
167	NJ_H_R2R43P04_A11_246_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
168	NJ_H_R2R43P07_A11_258_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
169	NJ_H_R2R43P09_A11_246_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
170	NJ_H_R2R43P11_A11_90_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
171	NJ_H_R2R44P01_A11_90_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
172	NJ_H_R2R44P06_A11_92_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
173	NJ_H_R2R44P11_A11_259_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
174	NJ_H_R2R45P01_A11_88_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
175	NJ_H_R2R45P04_A11_94_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
176	NJ_H_R2R45P06_DA3_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
177	NJ_H_R2R45P07_A11_259_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
178	NJ_H_R2R45P09_DA4_31	North Brunswick, NJ	July 2018	Tiller	7.6 cm
179	NJ_H_R2R45P10_A11_93_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
180	NJ_H_R2R46P02_A11_258_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
181	NJ_H_R2R46P03_A11_92_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
182	NJ_H_R2R46P05_A11_93_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
183	NJ_H_R2R46P10_A11_246_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
184	NJ_H_R2R46P12_A11_86_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
185	NJ_H_R2R47P01_A11_88_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
186	NJ_H_R2R47P02_A11_94_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
187	NJ_H_R2R47P05_DA4_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
188	NJ_H_R2R47P09_A11_93_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
189	NJ_H_R2R47P11_A11_90_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm

190	NJ_H_R2R48P01_DA3_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
191	NJ_H_R2R48P02_DA3_26	North Brunswick, NJ	July 2018	Tiller	7.6 cm
192	NJ_H_R2R48P08_DA4_16	North Brunswick, NJ	July 2018	Tiller	7.6 cm
193	NJ_H_R2R48P11_A11_93_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
194	NJ_H_R2R49P03_A11_86_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
195	NJ_H_R2R49P08_A11_259_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
196	NJ_H_R2R50P03_A11_92_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
197	NJ_H_R2R50P04_A11_259_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
198	NJ_H_R2R50P07_A11_246_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
199	NJ_H_R2R50P09_A11_258_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
200	NJ_H_R2R50P10_DA3_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
201	NJ_H_R2R51P01_A11_90_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
202	NJ_H_R2R51P05_A11_86_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
203	NJ_H_R2R51P06_DA4_24	North Brunswick, NJ	July 2018	Tiller	7.6 cm
204	NJ_H_R2R51P07_DA4_18	North Brunswick, NJ	July 2018	Tiller	7.6 cm
205	NJ_H_R2R51P10_DA3_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
206	NJ_H_R2R51P11_A11_88_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
207	NJ_H_R2R51P12_DA4_34	North Brunswick, NJ	July 2018	Tiller	7.6 cm
208	NJ_H_R2R52P04_A11_246_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
209	NJ_H_R2R52P10_A11_246_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
210	NJ_H_R2R52P11_A11_259_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
211	NJ_H_R2R52P12_A11_94_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
212	NJ_H_R2R53P01_DA3_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
213	NJ_H_R2R53P04_DA3_19	North Brunswick, NJ	July 2018	Tiller	7.6 cm

214	NJ_H_R2R53P06_DA4_19	North Brunswick, NJ	July 2018	Tiller	7.6 cm
215	NJ_H_R2R53P11_A11_94_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
216	NJ_H_R2R54P02_A11_258_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
217	NJ_H_R2R54P06_A11_90_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
218	NJ_H_R2R54P10_A11_246_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
219	F21A3(ck)071718P003_BM1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
220	F21A3(ck)071718P008_TE2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
221	F21A3(ck)071718P009_H575_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
222	F21A3(ck)071718P010_BM2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
223	F21A3(ck)071718p012_MNHD_12	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
224	F21A3(ck)071718p013_7H4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
225	F21A3(ck)071718p020_H571_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
226	F21A3(ck)071718p024_RELIANT_IV	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
227	F21A3(ck)071718p027_7H3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
228	F21A3(ck)071718p031_BRIGADE	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
229	F21A3(ck)071718p033_PPG_FL_102	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
230	F21A3(ck)071718p036_H571_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
231	F21A3(ck)071718p043_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
232	F21A3(ck)071718p044_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
233	F21A3(ck)071718p051_OXFORD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
234	F21A3(ck)071718p055_TE1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
235	F21A3(ck)071718p057_PREDATOR	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
236	F21A3(ck)071718p061_7H1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
237	F21A3(ck)071718p063_RESCUE_911	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

238	F21A3(ck)071718p064_7H6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
239	F21A3(ck)071718p065_7H5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
240	F21A3(ck)071718p066_7H2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
241	F21A3(ck)071718p067_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
242	F21A3(ck)071718p073_RELIANT_IV	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
243	F21A3(ck)071718p079_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
244	F21A3(ck)071718p083_PREDATOR	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
245	F21A3(ck)071718p086_RESCUE_911	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
246	F21A3(ck)071718p088_7H1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
247	F21A3(ck)071718p089_7H2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
248	F21A3(ck)071718p090_7H3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
249	F21A3(ck)071718p091_7H4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
250	F21A3(ck)071718p092_7H6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
251	F21A3(ck)071718p095_H573_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
252	F21A3(ck)071718p097_TE1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
253	F21A3(ck)071718p099_BM1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
254	F21A3(ck)071718p100_BM2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
255	F21A3(ck)071718p101_H575_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
256	F21A3(ck)071718p102_H571_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
257	F21A3(ck)071718p104_TE2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
258	F21A3(ck)071718p121_7H5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
259	F21A3(ck)071718p126_BRIDGADE	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
260	F21A3(ck)071718p128_OXFORD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
261	F21A3(ck)071718p129_OC1	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

262	F21A3(ck)071718p131_PPG_FL_102	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
263	F21A3(ck)071718p142_AURORA_GOLD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
264	F21A3(ck)071718p147_PPF_FL_102	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
265	F21A3(ck)071718p148_7H4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
266	F21A3(ck)071718p152_7H3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
267	F21A3(ck)071718p158_BM2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
268	F21A3(ck)071718p160_7H6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
269	F21A3(ck)071718p164_7H2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
270	F21A3(ck)071718p167_H571_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
271	F21A3(ck)071718p168_TE1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
272	F21A3(ck)071718p169_BRIGADE	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
273	F21A3(ck)071718p173_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
274	F21A3(ck)071718p176_H573_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
275	F21A3(ck)071718p179_OXFORD	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
276	F21A3(ck)071718p181_RESCUE_911	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
277	F21A3(ck)071718p183_TE2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
278	F21A3(ck)071718p184_MNHD_12	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
279	F21A3(ck)071718p186_7H1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
280	F21A3(ck)071718p188_PREDATOR	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
281	F21A3(ck)071718p189_BM1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
282	F21A3(ck)071718p192_RELIANT_IV	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
283	F21A3(ck)071718p194_7H5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
284	F21A3(ck)071718p196_H575_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

Table A.3 List of strong creeping red fescue used for near-infrared reflectance spectroscopy (NIRS) model development to predict total cell wall content, lignocellulose, hemicellulose, lignin, and cellulose.

No.	Sample ID	Location	Harvest Time	Type	Mowing Height
1	AdelphiaFF5Oct2017Plot041_FT6_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
2	AdelphiaFF5Oct2017Plot043_7C34	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
3	AdelphiaFF5Oct2017Plot050_NAVIGATOR_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
4	AdelphiaFF5Oct2017Plot041_FT9_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
5	AdelphiaFF5Oct2017Plot043_7C34	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
6	AdelphiaFF5Oct2017Plot050_NAVIGATOR_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
7	AdelphiaFF5Oct2017Plot041_FT9_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
8	AdelphiaFF5Oct2017Plot043_7C34	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
9	AdelphiaFF5Oct2017Plot050_NAVIGATOR_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
10	AdelphiaFF5Oct2017Plot041_FT9_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
11	AdelphiaFF5Oct2017Plot043_7C34	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
12	AdelphiaFF5Oct2017Plot050_NAVIGATOR_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
13	AdelphiaFF5Oct2017Plot041_FT9_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
14	AdelphiaFF5Oct2017Plot043_7C34	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
15	AdelphiaFF5Oct2017Plot050_NAVIGATOR_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
16	AdelphiaFF5Oct2017Plot041_FT9_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
17	AdelphiaFF5Oct2017Plot043_7C34	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
18	AdelphiaFF5Oct2017Plot050_NAVIGATOR_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
19	AdelphiaFF5Oct2017Plot041_FT9_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
20	AdelphiaFF5Oct2017Plot043_7C34	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
21	AdelphiaFF5Oct2017Plot050_NAVIGATOR_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm

22	AdelphiaFF5Oct2017Plot041_FT9_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
23	AdelphiaFF5Oct2017Plot136_5_12FF_6	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
24	AdelphiaFF5Oct2017Plot139_PPG_FRR103	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
25	AdelphiaFF5Oct2017Plot142_2_10FFR_13	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
26	AdelphiaFF5Oct2017Plot150_NAVIGATOR_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
27	AdelphiaFF5Oct2017Plot152_CRF_11A4A	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
28	AdelphiaFF5Oct2017Plot155-S571_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
29	AdelphiaFF5Oct2017Plot159_SEABREEZE_GT	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
30	AdelphiaFF5Oct2017Plot162_ORACLE	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
31	AdelphiaFF5Oct2017Plot163_2-10FRBULK	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
32	AdelphiaFF5Oct2017Plot164_SR5250	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
33	AdelphiaFF5Oct2017Plot165_SEA_FIRE	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
34	AdelphiaFF5Oct2017Plot166_SOILGUARD	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
35	AdelphiaFF5Oct2017Plot167_MES1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
36	AdelphiaFF5Oct2017Plot172_CARDINAL	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
37	AdelphiaFF5Oct2017Plot174_FT5_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
38	AdelphiaFF5Oct2017Plot179_OR_126	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
39	AdelphiaFF5Oct2017Plot180_FT3_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
40	AdelphiaFF5Oct2017Plot182_FT1_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
41	AdelphiaFF5Oct2017Plot183_BRSG	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
42	AdelphiaFF5Oct2017Plot184_5_12FF_5	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
43	AdelphiaFF5Oct2017Plot186_PSG_5RM	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
44	AdelphiaFF5Oct2017Plot188_JASPER_II	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
45	AdelphiaFF5Oct2017Plot200_FT6_COMP	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm

46	AdelphiaFF5Oct2017Plot220_4_12FF_BULK	Adelphia, NJ	Oct. 2017	Turf plot	6.4 cm
47	AdelphiaFF5Oct2017Plot223_SOILGUARD	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
48	AdelphiaFF5Oct2017Plot225_5_12FF_8	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
49	AdelphiaFF5Oct2017Plot230_SEA_FIRE	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
50	AdelphiaFF5Oct2017Plot234_4_12FF_1	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
51	AdelphiaFF5Oct2017Plot249_MES1_COMP	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
52	AdelphiaFF5Oct2017Plot253_SR5250	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
53	AdelphiaFF5Oct2017Plot263_7C3_COMP	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
54	AdelphiaFF5Oct2017Plot265_CROSSBOW_II	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
55	AdelphiaFF5Oct2017Plot298_7H2_COMP	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
56	AdelphiaFF5Oct2017Plot31_SEALINK	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
57	AdelphiaFF5Oct2017Plot32_SEA_FIRE	North Brunswick, NJ	Oct. 2017	Turf plot	6.4 cm
58	F21TrafficSep2017P006_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
59	F21TrafficSep2017P007_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
60	F21TrafficSep2017P018_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
61	F21TrafficSep2017P019_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
62	F21TrafficSep2017P022_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
63	F21TrafficSep2017P024_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
64	F21TrafficSep2017P034_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
65	F21TrafficSep2017P038_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
66	F21TrafficSep2017P046_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
67	F21TrafficSep2017P049_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
68	F21TrafficSep2017P053_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
69	F21TrafficSep2017P055_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

70	F21TrafficSep2017P061_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
71	F21TrafficSep2017P062_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
72	F21TrafficSep2017P073_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
73	F21TrafficSep2017P074_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
74	F21TrafficSep2017P083_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
75	F21TrafficSep2017P084_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
76	F21TrafficSep2017P091_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
77	F21TrafficSep2017P099_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
78	F21TrafficSep2017P103_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
79	F21TrafficSep2017P110_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
80	F21TrafficSep2017P111_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
81	F21TrafficSep2017P112_PPG_FRR_106	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
82	MN_S_B1C19R1_MES2_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
83	MN_S_B1C19R2_MES2_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
84	MN_S_B1C19R3_MES2_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
85	MN_S_B1C19R4_MES2_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
86	MN_S_B1C19R7_MES2_16	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
87	MN_S_B1C19R8_MES2_17	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
88	MN_S_B1C20R1_MES2_21	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
89	MN_S_B1C20R2_MES2_22	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
90	MN_S_B1C20R3_MES2_23	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
91	MN_S_B1C20R4_MES1_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
92	MN_S_B1C20R5_MES1_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
93	MN_S_B1C20R6_MES1_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm

94	MN_S_B1C20R7_MES1_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
95	MN_S_B1C21R4_A11_563_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
96	MN_S_B1C21R5_A11_563_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
97	MN_S_B1C21R6_A11_563_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
98	MN_S_B1C21R8_A11_563_10	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
99	MN_S_B1C22R1_A11_563_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
100	MN_S_B1C22R3_A11_564_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
101	MN_S_B1C22R5_A11_564_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
102	MN_S_B1C22R9_A11_564_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
103	MN_S_B1C23R2_MES2_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
104	MN_S_B1C23R3_MES2_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
105	MN_S_B1C23R4_MES2_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
106	MN_S_B1C23R6_MES2_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
107	MN_S_B1C23R7_MES2_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
108	MN_S_B1C23R8_MES2_13	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
109	MN_S_B1C23R9_MES2_18	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
110	MN_S_B1C24R3_A11_566_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
111	MN_S_B1C24R5_A11_566_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
112	MN_S_B1C24R6_A11_566_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
113	MN_S_B1C24R7_A11_566_9	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
114	MN_S_B1C24R9_A11_566_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
115	MN_S_B1C25R6_A11_565_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
116	MN_S_B1C25R7_A11_565_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
117	MN_S_B1C26R2_A11_564_10	St. Paul, MN	Aug. 2018	Tiller	7.6 cm

118	MN_S_B1C26R3A11_564_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
119	MN_S_B1C26R4A11_564_12	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
120	MN_S_B1C26R6_A11_565_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
121	MN_S_B1C26R8_A11_565_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
122	MN_S_B1C27R5_MES1_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
123	MN_S_B1C27R6_MES1_9	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
124	MN_S_B1C27R7_MES1_10	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
125	MN_S_B1C27R8_A11_20_1	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
126	MN_S_B1C28R2_A11_20_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
127	MN_S_B1C28R8_A11_20_10	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
128	MN_S_B1C28R9_A11_20_11	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
129	MN_S_B1C29R4_A11_28_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
130	MN_S_B1C29R5_A11_28_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
131	MN_S_B1C29R7_A11_28_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
132	MN_S_B1C29R8_A11_28_7	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
133	MN_S_B1C29R9_A11_28_8	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
134	MN_S_B1C31R7_A11_12_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
135	MN_S_B1C32R6_A11_12_10	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
136	MN_S_B1C33R1_A11_18_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
137	MN_S_B1C33R4_A11_18_5	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
138	MN_S_B1C34R4_OS3_2	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
139	MN_S_B1C34R5_OS3_3	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
140	MN_S_B1C34R6_OS3_4	St. Paul, MN	Aug. 2018	Tiller	7.6 cm
141	MN_S_B1C34R8_OS3_6	St. Paul, MN	Aug. 2018	Tiller	7.6 cm

142	NJ_S_R3P81P02_MES2_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
143	NJ_S_R3P81P05_MES1_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
144	NJ_S_R3P81P08_A11_18_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
145	NJ_S_R3P81P09_OS3_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
146	NJ_S_R3P81P12_A11_566_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
147	NJ_S_R3P82P02_A11_18_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
148	NJ_S_R3P82P12_A11_28_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
149	NJ_S_R3P83P04_A11_20_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
150	NJ_S_R3P83P05_A11_566_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
151	NJ_S_R3P83P07_MES2_19	North Brunswick, NJ	July 2018	Tiller	7.6 cm
152	NJ_S_R3P83P12_MES1_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
153	NJ_S_R3P84P01_OS3_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
154	NJ_S_R3P84P06_A11_18_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
155	NJ_S_R3P84P07_A11_12_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
156	NJ_S_R3P84P08_MES1_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
157	NJ_S_R3P84P12_A11_11_8	North Brunswick, NJ	July 2018	Tiller	7.6 cm
158	NJ_S_R3R85P03_A11_12_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
159	NJ_S_R3R85P04_MES2_18	North Brunswick, NJ	July 2018	Tiller	7.6 cm
160	NJ_S_R3R85P05_A11_566_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
161	NJ_S_R3R85P06_A11_11_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
162	NJ_S_R3R85P07_A11_12_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
163	NJ_S_R3R85P08_MES1_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
164	NJ_S_R3R85P10_A11_18_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
165	NJ_S_R3R85P12_A11_12_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm

166	NJ_S_R3R86P01_A11_565_2	North Brunswick, NJ	July 2018	Tiller	7.6 cm
167	NJ_S_R3R86P02_A11_18_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
168	NJ_S_R3R86P05_A11_11_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
169	NJ_S_R3R86P06_A11_28_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
170	NJ_S_R3R86P11_A11_20_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
171	NJ_S_R3R87P04_MES2_7	North Brunswick, NJ	July 2018	Tiller	7.6 cm
172	NJ_S_R3R87P05_A11_566_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
173	NJ_S_R3R87P09_A11_20_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
174	NJ_S_R3R88P02_A11_12_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
175	NJ_S_R3R88P03_OS3_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
176	NJ_S_R3R88P06_MES2_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
177	NJ_S_R3R88P07_A11_20_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
178	NJ_S_R3R88P08_MES2_17	North Brunswick, NJ	July 2018	Tiller	7.6 cm
179	NJ_S_R3R88P11_MES1_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
180	NJ_S_R3R88P12_MES2_13	North Brunswick, NJ	July 2018	Tiller	7.6 cm
181	NJ_S_R3R89P01_A11_566_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
182	NJ_S_R3R89P04_A11_564_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
183	NJ_S_R3R89P05_A11_28_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
184	NJ_S_R3R89P11_A11_20_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
185	NJ_S_R3R90P02_MES2_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
186	NJ_S_R3R90P03_A11_563_10	North Brunswick, NJ	July 2018	Tiller	7.6 cm
187	NJ_S_R3R90P05_A11_566_5	North Brunswick, NJ	July 2018	Tiller	7.6 cm
188	NJ_S_R3R90P06_MES2_1	North Brunswick, NJ	July 2018	Tiller	7.6 cm
189	NJ_S_R3R90P10_A11_11_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm

190	NJ_S_R3R90P12_A11_18_6	North Brunswick, NJ	July 2018	Tiller	7.6 cm
191	NJ_S_R4R91P02_A11_18_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
192	NJ_S_R4R91P03_MES1_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
193	NJ_S_R4R91P04_A11_564_4	North Brunswick, NJ	July 2018	Tiller	7.6 cm
194	NJ_S_R4R91P08_OS3_3	North Brunswick, NJ	July 2018	Tiller	7.6 cm
195	NJ_S_R4R92P01_A11_564_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
196	NJ_S_R4R92P02_MES2_22	North Brunswick, NJ	July 2018	Tiller	7.6 cm
197	NJ_S_R4R92P06_A11_565_9	North Brunswick, NJ	July 2018	Tiller	7.6 cm
198	NJ_S_R4R92P11_A11_565_12	North Brunswick, NJ	July 2018	Tiller	7.6 cm
199	NJ_S_R4R92P12_A11_565_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
200	NJ_S_R4R93P04_OS3_11	North Brunswick, NJ	July 2018	Tiller	7.6 cm
201	F21A3(ck)071718P001_BEACON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
202	F21A3(ck)071718P002_EPIC	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
203	F21A3(ck)071718P006_CINDY_LOU	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
204	F21A3(ck)071718P011_CHANTILLY	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
205	F21A3(ck)071718p014_S571_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
206	F21A3(ck)071718p015_PENN_ASC_295	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
207	F21A3(ck)071718p017_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
208	F21A3(ck)071718p021_7C1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
209	F21A3(ck)071718p025_S572_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
210	F21A3(ck)071718p028_7C4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
211	F21A3(ck)071718p029_MISER	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
212	F21A3(ck)071718p032_FT-4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
213	F21A3(ck)071718p035_7C5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

214	F21A3(ck)071718p037_FT_2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
215	F21A3(ck)071718p039_7C6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
216	F21A3(ck)071718p041_NAVIGATOR_II	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
217	F21A3(ck)071718p042_7C2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
218	F21A3(ck)071718p046_FT_5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
219	F21A3(ck)071718p048_7C3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
220	F21A3(ck)071718p052_FT_1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
221	F21A3(ck)071718p056_FT_6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
222	F21A3(ck)071718p058_AUDUBON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
223	F21A3(ck)071718p070_CHANTILLY	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
224	F21A3(ck)071718p074_MISER	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
225	F21A3(ck)071718p076_CINDY_LOU	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
226	F21A3(ck)071718p082_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
227	F21A3(ck)071718p084_NAVIGATOR_II	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
228	F21A3(ck)071718p085_AUDUBON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
229	F21A3(ck)071718p098_S572_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
230	F21A3(ck)071718p103_S571_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
231	F21A3(ck)071718p105_FT_2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
232	F21A3(ck)071718p107_FT_6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
233	F21A3(ck)071718p108_ FT_1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
234	F21A3(ck)071718p109 _FT_3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
235	F21A3(ck)071718p110_ FT_5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
236	F21A3(ck)071718p111_ FT_4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
237	F21A3(ck)071718p113_7C1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

238	F21A3(ck)071718p114_7C2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
239	F21A3(ck)071718p115_7C3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
240	F21A3(ck)071718p116_7C4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
241	F21A3(ck)071718p117_7C5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
242	F21A3(ck)071718p118_7C6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
243	F21A3(ck)071718p124_PENN_ASC_295	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
244	F21A3(ck)071718p127_EPIC	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
245	F21A3(ck)071718p134_7C5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
246	F21A3(ck)071718p141_FT_6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
247	F21A3(ck)071718p145_NAVIGATOR_II	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
248	F21A3(ck)071718p149_S571_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
249	F21A3(ck)071718p151_CINDY_LOU	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
250	F21A3(ck)071718p154_7C5_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
251	F21A3(ck)071718p157_GARNET	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
252	F21A3(ck)071718p159_ FT_3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
253	F21A3(ck)071718p161_MISER	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
254	F21A3(ck)071718p162_EPIC	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
255	F21A3(ck)071718p163_PENN_ASC_295	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
256	F21A3(ck)071718p166_CHANTILLY	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
257	F21A3(ck)071718p170_7C2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
258	F21A3(ck)071718p175_FT_2_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
259	F21A3(ck)071718p178_S572_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
260	F21A3(ck)071718p180_FT_4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
261	F21A3(ck)071718p187_ FT_1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

262	F21A3(ck)071718p190_7C3_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
263	F21A3(ck)071718p191_7C1_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
264	F21A3(ck)071718p193_7C6_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
265	F21A3(ck)071718p197_7C4_COMP	North Brunswick, NJ	July 2018	Turf plot	6.4 cm
266	F21A3(ck)071718p198_AUDUBON	North Brunswick, NJ	July 2018	Turf plot	6.4 cm

Table A. 4 List of Chewings fescue used for near-infrared reflectance spectroscopy (NIRS) model development to predict total nitrogen.

No.	Sample ID	Location	Harvest Time	Type	Mowing Height
1	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
2	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
3	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
4	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
5	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
6	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
7	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
8	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
9	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
10	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
11	Rushmore	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
12	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
13	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
14	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
15	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
16	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
17	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
18	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
19	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
20	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
21	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
22	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
23	Rushmore	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
24	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
25	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm

26	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
27	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
28	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
29	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
30	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
31	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
32	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
33	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
34	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
35	Rushmore	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
36	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
37	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
38	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
39	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
40	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
41	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
42	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
43	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
44	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
45	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
46	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
47	Rushmore	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
48	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
49	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
50	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
51	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
52	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm

53	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
54	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
55	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
56	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
57	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
58	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
59	Rushmore	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
60	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
61	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
62	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
63	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
64	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
65	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
66	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
67	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
68	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
69	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
70	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
71	Rushmore	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm

Table A.5 List of hard fescue used for near-infrared reflectance spectroscopy (NIRS) model development to predict total nitrogen.

No.	Sample ID	Location	Harvest Time	Type	Mowing Height
1	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
2	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
3	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
4	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
5	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
6	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
7	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
8	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
9	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
10	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
11	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
12	Beacon	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
13	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
14	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
15	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
16	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
17	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
18	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
19	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
20	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
21	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
22	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
23	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
24	Beacon	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
25	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm

26	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
27	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
28	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
29	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
30	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
31	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
32	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
33	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
34	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
35	Beacon	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
36	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
37	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
38	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
39	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
40	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
41	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
42	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
43	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
44	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
45	Beacon	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
46	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
47	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
48	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
49	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
50	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
51	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
52	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm

53	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
54	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
55	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
56	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
57	Beacon	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
58	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
59	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
60	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
61	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
62	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
63	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
64	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
65	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
66	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
67	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm
68	Beacon	North Brunswick, NJ	Oct 2015	Turf plot	6.4 cm

Table A.6 List of strong creeping red fescues used for near-infrared reflectance spectroscopy (NIRS) model development to predict total nitrogen.

No.	Sample ID	Location	Harvest Time	Type	Mowing Height
1	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
2	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
3	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
4	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
5	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
6	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
7	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
8	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
9	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
10	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
11	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
12	Garnet	North Brunswick, NJ	May 2016	Turf plot	6.4 cm
13	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
14	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
15	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
16	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
17	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
18	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
19	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
20	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
21	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
22	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
23	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm
24	Garnet	North Brunswick, NJ	July 2016	Turf plot	6.4 cm

25	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
26	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
27	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
28	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
29	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
30	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
31	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
32	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
33	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
34	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
35	Garnet	North Brunswick, NJ	Nov. 2016	Turf plot	6.4 cm
36	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
37	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
38	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
39	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
40	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
41	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
42	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
43	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
44	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
45	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
46	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
47	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
48	Garnet	North Brunswick, NJ	May 2015	Turf plot	6.4 cm
49	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
50	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
51	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm

52	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
53	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
54	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
55	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
56	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
57	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
58	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
59	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
60	Garnet	North Brunswick, NJ	June 2015	Turf plot	6.4 cm
61	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
62	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
63	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
64	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
65	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
66	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
67	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
68	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
69	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
70	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
71	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm
72	Garnet	North Brunswick, NJ	Oct. 2015	Turf plot	6.4 cm

APPENDIX B

Table B.1 List of fine fescues used in Study 1 for the evaluation of correlation between verdure biomass and cell wall constitutions to wear tolerance (samples collected from Adelphia, NJ in October 2017)

Chewings fescue (n=18)	Hard fescue (n=26)	Strong creeping red fescue (n=13)
4CHY	4BND	2-10FRR-13
4SHR-CH	7H1 COMP	2-10FRRBULK
7W1 COMP	7H2 COMP	4-12FF-3
7W2 COMP	7H2 COMP	4-12FF-BULK
7W3 COMP	7H3 COMP	7C3 COMP
AMBROSE	7H4	CRF-11-4A
FAIRMONT	7H4 COMP	FT6 COMP
MEW1 COMP	7H6 COMP	MES1 COMP
MEW2 COMP	7HF	NAVIGATOR II
PPG-FRC 103	BEACON	OR 126
PPG-FRC 107	BM2 COMP	S571 COMP
PPG-FRC 113	H571 COMP	SOILGUARD
PPG-FRC 114	H573 COMP	SR5250
PPG-FRC 115	H575 COMP	
PSG 50C3	MEH1 COMP	
RADAR	MEH2 COMP	
SR5 130	OXFORD	
WINDWARD	PPG-FL 106	
	PPG-FL 107	
	PPG-FL 108	
	PREDATOR	
	PSG TH3	
	RELIANT IV	
	SPARTAN II	
	TE1 COMP	
	TE2 COMP	

Table B.2 List of fine fescues used in Study 2 for the evaluation of correlation between verdure biomass and cell wall constitutions to wear tolerance (samples collected from North Brunswick, NJ in July 2018)

Chewings fescue (n=16)	Hard fescue (n=14)	Strong creeping red fescue (n=22)
7W2 COMP	7H1 COMP	7C1 COMP
7W3 COMP	7H4 COMP	7C2 COMP
AMBASSADOR	AURORA GOLD	7C3 COMP
AMBROSE	BM1 COMP	7C4 COMP
C571 COMP	BM2 COMP	7C5 COMP
C572 COMP	BRIGADE	7C6 COMP
CULUMBRA II	H571 COMP	AUDUBON
J-5	H573 COMP	CHANTILLY
KOKET	H575 COMP	CINDY LOU
LONGFELLOW 3	PPG FL 102	EPIC
LONGFELLOW II	PREDATOR	FFR-102
OC1	TE1 COMP	FT-1 COMP
RUSHMORE	TE2 COMP	FT-2 COMP
SHADOW II		FT-3 COMP
SURVIVOR		FT-4 COMP
		FT-5 COMP
		FT-6 COMP
		GARNET
		MISER
		NAVIGATOR II
		PENN ASC 295
		S571 COMP
		S572 COMP

Table B.3 List of fine fescues used in Study 3 for the evaluation of correlation between verdure biomass and cell wall constitutions to wear tolerance (samples collected from North Brunswick, NJ in July 2018)

Chewings fescue (n=61)	Hard fescue (n=61)	Strong creeping red fescue (n=62)
3W1_10	A_246_10	A_11_11
3W1_12	A_246_12	A_11_5
3W1_19	A_246_3	A_11_8
3W1_26	A_246_4	A_11_9
3W1_28	A_246_6	A_12_10
3W1_31	A_246_7	A_12_12
3W1_36	A_246_9	A_12_2
3W1_37	A_258_10	A_12_4
3W1_38	A_258_4	A_12_5
3W1_43	A_258_6	A_18_10
3W1_48	A_258_9	A_18_11
3W1_50	A_259_12	A_18_2
3W1_8	A_259_2	A_18_3
3W2_1	A_259_4	A_18_5
3W2_10	A_259_8	A_18_6
3W2_11	A_259_9	A_18_7
3W2_16	A_86_1	A_20_1
3W2_18	A_86_10	A_20_12
3W2_20	A_86_11	A_20_4
3W2_3	A_86_12	A_20_6
3W2_5	A_88_2	A_20_7
3W2_7	A_88_5	A_20_9
3W3_10	A_88_6	A_28_10
3W3_21	A_90_1	A_28_8
3W3_22	A_90_11	A_28_9
3W3_24	A_90_12	A_563_10
3W3_28	A_90_2	A_564_12
3W3_31	A_90_4	A_564_2

3W3_7	A_90_7	A_564_4
3W3_8	A_92_1	A_564_5
A_437_5	A_92_10	A_565_11
A_437_6	A_92_11	A_565_12
A_438_5	A_93_4	A_565_2
A_438_6	A_93_6	A_565_3
A_439_4	A_93_8	A_565_9
A_439_5	A_93_9	A_566_11
A_439_8	A_94_11	A_566_3
A_440_2	A_94_2	A_566_4
A_440_6	A_94_3	A_566_8
A_48_1	A_94_5	A_566_9
A_48_2	A_94_8	MES1_3
A_48_6	A_94_9	MES1_5
A_48_8	DA3_1	MES1_6
A_50_10	DA3_11	MES1_7
A_50_11	DA3_12	MES1_8
A_50_12	DA3_19	MES1_9
A_50_3	DA3_26	MES2_1
A_50_5	DA3_3	MES2_12
A_50_6	DA3_4	MES2_13
A_50_9	DA3_7	MES2_16
A_51_1	DA3_9	MES2_17
A_51_4	DA4_1	MES2_18
A_51_6	DA4_11	MES2_19
A_51_8	DA4_16	MES2_2
A_70_3	DA4_18	MES2_22
A_70_7	DA4_19	MES2_4
A_74_11	DA4_24	MES2_7
A_74_4	DA4_3	OS3_1
A_74_6	DA4_31	OS3_10
A_74_7	DA4_34	OS3_11

A_74_9	DA4_4	OS3_3
		OS3_4

Table B.4 List of fine fescues used in Study 4 for the evaluation of correlation between verdure biomass and cell wall constitutions to wear tolerance (samples collected from St. Paul, MN in August 2018)

Chewings fescue (n=51)	Hard fescue (n=39)	Strong creeping red fescue (n=23)
3W1_10	A_246_4	A_12_2
3W1_12	A_246_5	A_18_2
3W1_15	A_246_6	A_18_5
3W1_26	A_246_7	A_20_1
3W1_28	A_246_9	A_563_12
3W1_36	A_258_3	A_564_12
3W1_37	A_258_9	A_564_2
3W1_38	A_259_2	A_564_4
3W1_40	A_259_4	A_565_11
3W1_42	A_259_8	MES1_1
3W1_48	A_259_9	MES1_2
3W1_5	A_88_1	MES2_1
3W1_50	A_88_12	MES2_11
3W1_8	A_88_2	MES2_16
3W2_1	A_88_3	MES2_17
3W2_11	A_88_5	MES2_22
3W2_18	A_90_1	MES2_5
3W2_3	A_90_11	MES2_7
3W2_5	A_90_12	OS3_10
3W2_7	A_90_2	OS3_11
3W3_10	A_90_4	OS3_3
3W3_21	A_90_7	OS3_4
3W3_28	A_90_9	OS3_6
3W3_31	A_92_1	
3W3_7	A_93_6	
3W3_8	A_94_2	
A_437_1	A_94_3	
A_437_6	A_94_7	
A_438_11	A_94_9	

A_439_11	DA3_1	
A_439_5	DA3_11	
A_439_8	DA3_13	
A_439_9	DA3_19	
A_48_8	DA3_4	
A_50_11	DA3_7	
A_50_12	DA4_18	
A_50_5	DA4_19	
A_50_6	DA4_31	
A_50_7	DA4_8	
A_50_9		
A_51_1		
A_51_10		
A_51_4		
A_51_8		
A_70_3		
A_70_4		
A_74_11		
A_74_12		
A_74_2		
A_74_6		
A_74_7		