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Modeling Emergence of Annual Bluegrass (Poa annua L.) in Hybrid Bermudagrass [C. dactylon (L.) Pers. x C. transvaalensis Burtt-Davy]

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To the Graduate Council:

I am submitting herewith a thesis written by Dallas Rose Taylor entitled "Modeling Emergence of Annual Bluegrass (Poa annua L.) in Hybrid Bermudagrass [C. dactylon (L.) Pers. x C. transvaalensis Burtt-Davy]." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

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Modeling Emergence of Annual Bluegrass *(Poa annua* L.*)* in Hybrid Bermudagrass [*C. dactylon* (L.) Pers. *x C. transvaalensis* Burtt-Davy]

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Dedication

To my dog and best friend, Ghostbuster. Thank you for pushing me to do my best and staying up with me on the long nights.

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Abstract

Annual bluegrass (*Poa annua* L.; ABG) is a troublesome weed of turfgrass systems. A model to predict ABG emergence patterns could aid in timing measures to control ABG. Field research was initiated in January 2019 at the East Tennessee AgResearch & Education Center (ETREC) (Knoxville, TN) to better understand environmental conditions associated with ABG emergence. Plots (1 m^2) included both hybrid bermudagrass [*C. dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy, cv. 'Tifway', at a 1.5 cm cutting height] and bare soil. Emerged ABG inside a 1000 cm^2 area in the center of each plot was counted weekly for 10 months; during June and July ABG was counted biweekly. Sensors in each plot captured air temperature data on 15-minute intervals. Air temperature data were expressed as cooling degree days accumulated after 21 June (i.e., the summer solstice) using a 21 C base temperature (CDD_{21C}). Python (v.3.8.7) was used (post-hoc) to fit non-linear functions to ABG emergence and CDD_{21C} data collected in 2019; models were then tested for validation in 2020. Fluctuations in CDD_{21C} accounted for ≥ 82% of the variance in yearly cumulative ABG emergence at ETREC over two seasons. Although ABG emergence was first noted at a similar CDD_{21C} benchmark each year (12 CDD_{21C} in 2019 and 8 CDD_{21C} in 2020), a yearly cumulative emergence model underpredicted 50 and 75% emergence in 2020. Peak ABG emergence occurred during a 4-week period in both 2019 and 2020; however, the timing of this 4-week period varied over years. Future research should be conducted using the 24-month dataset generated herein to develop new ABG emergence models using both CDD_{21C} and rainfall accumulation.

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Section I
Literature Review

Annual Bluegrass Distribution

Annual bluegrass (*Poa annua* L.) is a difficult weed to control in all turfgrass systems. Its light green appearance causes a visual break in uniformity of turfgrass, particularly warm-season species such as bermudagrass (*Cynodon* spp.) and zoysiagrass (*Zoysia* spp.) during winter dormancy (Gibeault and Goetez 1973). Annual bluegrass has a shallow root system and is tolerant of both wet and compacted soils and can grow in both open or partially shaded areas (Gibeault and Goetez 1973). Annual bluegrass is a global weed problem as the species has been documented on all continents including Antarctica (Olech 1996). Since the plant was first recorded in Antarctica, it has steadily increased in response to the growing number of human populations on the continent (Chwedorzewska 2008). Human activity contributes to annual bluegrass establishment due to increased soil disturbance creating a more ideal growing habitat for the species.

Varieties of Annual Bluegrass

Two varieties of annual bluegrass are found throughout the United States, *Poa annua* var. *annua* and *Poa annua* var. *reptans* (Gibeault and Goetze 1973). According to Gibeault (1971), the perennial variety, *Poa annua* var. *reptans,* has more leaves, nodes, and adventitious roots than the annual variety, *Poa annua* var. *annua*. However, *Poa annua* var. *annua* possesses a greater percentage of flowering tillers and reaches reproductive maturity faster than *Poa annua* var. *reptans*. Research conducted by Johnson and White (1997a) found that seed of *Poa annua* var. *annua* does not respond to vernalization, whereas vernalization temperatures of ≤ 8 °C for 12 d are required for *Poa annua* var. *reptans* (Johnson and White 1997b).

Poa annua var. *reptans* is thought to be a perennial whereas *Poa annua* var. *annua* is an annual weed in the transition zone and southern United States. This relationship is supported by work of Till-Bottraud et al. (1990) who found that annual bluegrass from environments with low survival rates (e.g., warm summer air temperatures) favor annual strategies. According to Warwick and Briggs (1978), annual bluegrass with higher adult mortality rates puts more energy into flower production, therefore producing more seeds and increasing the population of that genotype. According to Lush (1989), high levels of seed production allow annual bluegrass to persist in turfgrass systems for numerous years. *Poa annua* var. *reptans* possesses no seed dormancy, however, it was recorded that *Poa annua* var. *annua* requires 2 to 3 months of seed dormancy before germination (Gibeault 1971). This dormancy typically occurs during the summer season when air temperatures are not favorable for annual bluegrass growth. That said, seed dormancy patterns have been found to vary among *Poa annua* var. *annua* ecotypes (McElroy et al. 2002). Given that *Poa annua* var. *annua* is the most prevalent annual bluegrass variety in Tennessee, *Poa annua* var. *annua* will be delineated hereafter as simply *Poa annua.*

Annual Bluegrass Germination Requirements

One reason for the widespread distribution of annual bluegrass is the species' ability to germinate under variable environmental conditions. According to Johnson and White (1997a), annual bluegrass is a day-neutral flowering plant. This claim was furthered by Itoh et al. (1997) who observed annual bluegrass germination (>70%) under conditions of complete darkness. Additional laboratory research by McElroy et al. (2004) confirmed this finding; the researchers reported that germination of eight annual bluegrass ecotypes under complete darkness (0 h day/ 24 h night) was similar to a photoperiod of 18 h day/6 h night. Moreover, McElroy et al. (2004) reported annual bluegrass germination was possible at air temperatures ranging from 10 to 39 °C.

However, the researchers noted that that annual bluegrass germination was optimal (93 to 97% germination of eight ecotypes) at air temperatures of 19 °C during the day and 10 °C during the evening. Historical climate data (1981 to 2010) illustrate that these benchmark air temperatures occur from October-November and March-April in Tennessee (Southeast Regional Climate Center 2019).

Emergence Timing

Previous research regarding annual bluegrass emergence under field conditions has reached variable conclusions. For example, in research exploring efficacy of bensulide for annual bluegrass control, Callahan and McDonald (1992) noted that annual bluegrass emergence in a creeping bentgrass (*Agrostis stolonifera* var. 'Penncross') putting green in Tennessee occurred during mid-to-late November, with the majority of annual bluegrass germinating by early January. On the contrary, Kaminski and Dernoeden (2007) monitored annual bluegrass emergence patterns in golf course roughs in Maryland and noted multiple emergence events from September through the following May. Peak emergence of annual bluegrass was recorded at the end of September when mean daily air temperatures measured $\leq$ 20 °C. Kaminski and Dernoeden (2007) observed that 50 to 70% of the total number of annual bluegrass seedlings emerged during a 3-to-4-week period during late September through October, while the remaining 30 to 50% of annual bluegrass emerged between the months of November through May. It is important to note that neither soil moisture nor soil temperature were evaluated in these field studies. Future field research should monitor these variables (in addition to air temperature) to better understand variability in annual bluegrass emergence patterns and potentially generate a prediction model to aid turfgrass managers. Masin and Macolino (2016) suggested that a single model to describe annual bluegrass emergence was appropriate after observing similar annual bluegrass emergence dynamics in newly established stands of perennial ryegrass (*Lolium perenne* L.) in years of variable soil temperature and moisture. Interestingly, no differences in annual bluegrass emergence were detected among plots established with perennial ryegrass and bare soil when precipitation was abundant. However, exact amounts of soil moisture were not reported.

Soil Seedbank Management

A model to better understand seedling emergence dynamics could help to manage herbicide resistance in annual bluegrass as soil seedbank management is a best management practice for resistance (Norsworthy et al. 2012). Annual weeds, such as annual bluegrass, are more prone to develop herbicide resistance than their perennial counterparts. Numerous cases of annual bluegrass evolving resistance to herbicidal inhibitors of mitosis, acetolactate synthase (ALS), photosystem II (PSII), or 5- enolyptuvylshikimate-3-phosphate synthetase (EPSPS) have been reported (Isgrigg et al. 2002; McElroy et al. 2013; Brosnan et al. 2012; Hutto et al. 2004; Brosnan et al. 2015; Breeden et al. 2017). Norsworthy et al. (2012) explained that failure to understand emergence dynamics from the soil seedbank can worsen herbicide resistance issues. Improperly timed preemergence applications can result in weed populations being exposed to sub-lethal doses of both pre- and postemergence herbicides, therefore increasing selection pressure for herbicide resistance.

Predictive Modeling in Turfgrass

Numerous efforts have been made to develop predictive models to assist practitioners with pest management applications in turfgrass. For example, growing degree day (GDD) accumulation (after April 1st) has been used to model annual bluegrass seed head formation with peaks occurring from 363 to 433 GDD_{13C} and declining thereafter (Danneberger and Vargas

1984). A limitation of this model is that it is specific to the north central United States and has not been validated in other geographic locations. Danneberger et al. (1987) later used this model to optimize efficacy of mefluidide applications for annual bluegrass seed head suppression. Peak seed head suppression was recorded with mefluidide applications at 15, 25, and 30 GDD_{13C}. Application of mefluidide at 45 GDD_{13C} resulted in seed head numbers that were 1.8 to 3.0 times greater than treatment at 30 GDD_{13C}. The 45 and 30 GDD_{13C} mefluidide application timings were recorded two days apart, which speaks to the value of using climatic data to time applications rather than calendar-based scheduling.

Kreuser and Soldat (2011) created a GDD model to schedule trinexapac-ethyl (TE) applications to creeping bentgrass putting greens. A three-parameter sine function was fit to clipping yield data collected over a span of GDD_{0C} accumulation. This model identified the growth phases (suppression or rebound) following TE treatment at different application intervals to elucidate regimes that maintained season-long yield suppression. Peak clipping yield suppression (18.3%) occurred 122 GDD_{0C} after TE treatment. Rebound growth began at 312 GDD_{0C}, peaked at 541 GDD_{0C}, with TE effects dissipating by 700 to 800 GDD_{0C}. Researchers found yield suppression of creeping bentgrass was most successful with re-applications made following the accumulation of 200 GDD_{0C}.

Reasor et al. (2018) built on the efforts of Kreuser and Soldat (2011) to develop a model to assist with plant growth regulator (PGR) applications on ultradwarf hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy) putting greens. GDD_{10C} were accumulated after application of TE or prohexadione-calcium to understand the degree and length of clipping yield reduction following treatment. Daily clipping yield and GDD_{10C} data were fit to sinewave models for both TE and prohexadione-calcium. Peak growth suppression with TE was observed between 166 GDD_{10C} and 177 GDD_{10C}. Comparatively, peak growth suppression with prohexadione-calcium occurred between 92 GDD_{10C} and 97 GDD_{10C}. Given that there was minimal rebound with either PGR, Reasor et al. (2018) determined that optimal re-application timings for TE and prohexadione-calcium were 216-230 GDD_{10C} and 120-126 GDD_{10C}, respectively.

A predictive model for smooth crabgrass (*Digitaria ischaemum* Schreb.) emergence in cool-season turfgrass was developed by Fidanza et al. (1996). During 1992 to 1994 in Maryland, the researchers counted (and removed) emerged smooth crabgrass seedlings from April 1st to August 31st to identify GDD_{12C} benchmarks associated with peak emergence. Smooth crabgrass emergence data were regressed over soil temperature and GDD_{12C} accumulated from April 1st. Peak smooth crabgrass emergence occurred between 140 to 230 GDD_{12C}. This model has proven useful in helping turfgrass managers apply preemergence herbicides for smooth crabgrass control at optimal timings in Maryland.

A model was developed to aid turfgrass managers in making fungicide applications to control dollar spot (*Clarireedia homoeocarpa*) in creeping bentgrass (Smith et al. 2018). The researchers monitored dollar spot outbreaks at multiple locations over an eight-year period to determine that the probability of an outbreak could be predicted using a logistic model that tracked a five-day moving average of daily relative humidity and daily average air temperature. The logistic-based model was developed by researchers to reduce yearly fungicide applications for dollar spot management compared to treating on a calendar-based schedule.

A goosegrass [*Eleusine indica* L. Gaertn.] emergence model was developed by Elmore et al. (2018) to predict seedling emergence patterns in cool-season turfgrass in New Jersey. The two-year study was initiated in April 2017 at a bare soil site as well as sites established to cool-season turfgrass managed at fairway (1.25 cm) and rough heights (6.4 cm). Emerged goosegrass plants were counted and removed from collection areas on a weekly basis, with fluctuations in soil temperature and moisture recorded for the duration of the data collection period. Season-long emergence rates revealed the bare soil treatment contained the greatest number of emerged seedlings, whereas plots maintained at rough height contained the fewest number of goosegrass seedlings. Non-linear models were developed to predict season long goosegrass emergence. Results showed similar patterns in the total yearly emergence rates between the bare soil and the cool-season turfgrass environment (pooled over height of cut). Regardless of environment (i.e., bare soil, 1.25 cm height, 6.4 cm height) peak emergence occurred on June 20. There was slight variation among emergence thresholds among the three different environments studied. For example, 65% goosegrass emergence for bare soil, fairway, and rough height turfgrass occurred on July 4, July 25, and July 15, 2017, respectively. The 90% yearly emergence threshold was reached on August 4, August 13, and August 12 for bare soil, fairway, and rough height turf, respectively.

Predictive Modeling in Other Agricultural Systems

Researchers in North Dakota developed a GDD model to assist in predicting soybean [*Glycine max* (L.) Merr.] maturity to facilitate harvesting prior to exposure to freezing temperatures in autumn (Akyuz et. al 2017). This nine-year research study consisted of 10 research sites in North Dakota and northern Minnesota. Planting and maturity dates were recorded at each location with GDD_{10C} accumulated thereafter and fit to linear regression models. These models were used to test predicted maturity dates against observed in-field maturity dates. The model proved to be reliable to growers when soybean planting dates fell between May 15 and 31. Researchers noted the importance of choosing a soybean cultivar suitable for the grower's location in order for the model to be as accurate as possible.

Bagavathiannan et al. (2011) used hydrothermal time data to model emergence patterns of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], another annual grassy weed that has evolved resistance to multiple herbicide modes of action in agronomic crops (Heap 2020). A four-parameter Weibull function was fit to barnyardgrass emergence, GDD, and hydrothermal time (i.e., soil moisture and soil temperature) data. GDD proved to be more reliable in predicting barnyardgrass emergence than hydrothermal time. Prolonged emergence events began in mid-April and with 100% emergence occurring in late September. Researchers concluded that peak emergence periods were dependent on the intensity of rainfall and soil temperature. The GDD model was able to identify 3-to-4 yearly barnyardgrass emergence cycles, following the presence of rainfall events. Importantly, the GDD model was able to identify peak emergence periods that would be optimal timings for herbicide applications. However, researchers concluded that herbicide applications based on calendar date were more effective at controlling barnyardgrass than herbicide applications made using the GDD model.

The majority of models developed for use in turfgrass and agricultural production have been generated using frequentist methodology. However, there is evidence that Bayesian approaches to model development, specifically the use of Artificial Neural Networks (ANNs) may be more advantageous (Chantre et al. 2012). For example, researchers in Argentina found that ANN-derived models were better able to describe wild oat (*Avena fatua* L.) seedling emergence than traditional non-linear regression techniques, in large part because they could capture changes in a multitude of environmental input variables in combination with one another.

The study found that non-linear models were inaccurate in predicting emergence, whereas thermal-time and hydro-time based ANN model were more advantageous.

Better understanding annual bluegrass emergence patterns could aid in resistance management by allowing turfgrass managers to optimally time applications to control populations either pre- or postemergence via chemical, cultural, or mechanical means. The objective of this research is to model the emergence of annual bluegrass in hybrid bermudagrass [*C. dactylon* (L.) Pers. x *C. transvaalensis* Burtt Davy]. Fluctuations in air temperature, soil temperature, and soil moisture could affect annual bluegrass emergence patterns in hybrid bermudagrass and be used to develop a predictive model to assist turfgrass managers with timing control measures.

Section II
Materials and Methods

Overview

Field research was conducted at the East Tennessee AgResearch and Education Center-Plant Sciences Unit (ETREC; Knoxville, TN; 35.90 °N, -83.95 °W) from January 2019 through December 2020. The research site was located 255 meters above sea level. Annual bluegrass emergence was monitored in a hybrid bermudagrass (cv. 'Tifway') fairway maintained at 1.5 cm with a reel mower during periods of active growth; the site was not mowed during winter dormancy. This research site has a natural history of herbicide-susceptible annual bluegrass infestation. Soil was a Sequatchie silt loam (fine-loamy, siliceous, semiactive, thermic humic Hapludult) with soil pH 6.2 and water pH 6.1. Phosphorus (Mehlich-I), potassium, calcium, and magnesium concentrations in soil measured 11, 73, 970, and 106 ppm, respectively.

Methods in this experiment were similar to those used by Elmore et al. (2018) to monitor goosegrass emergence in cool-season turfgrass. Plots (1 m x 1 m) were arranged in randomized complete block design (RCBD) with four replications. Within each replication, one plot was maintained as bare soil while the other was maintained as a hybrid bermudagrass (Figure 1). The two treatments were chosen because of the interest in emergence over the widest span of possible turfgrass conditions. Bare-soil plots were maintained by physically removing aboveground hybrid bermudagrass biomass via scalping prior to the start of the experiment and periodically applying glyphosate at 1120 g ha^{-1} (Roundup Pro. Bayer Environmental Sciences. St. Louis, MO) after collecting annual bluegrass emergence data.

Annual bluegrass emergence was monitored inside a circle (1000 cm^2) in the center of each plot. When an emerged annual bluegrass seedling was present inside the circle, it was recorded, and then discarded with tweezers. Emerged weeds other than annual bluegrass were

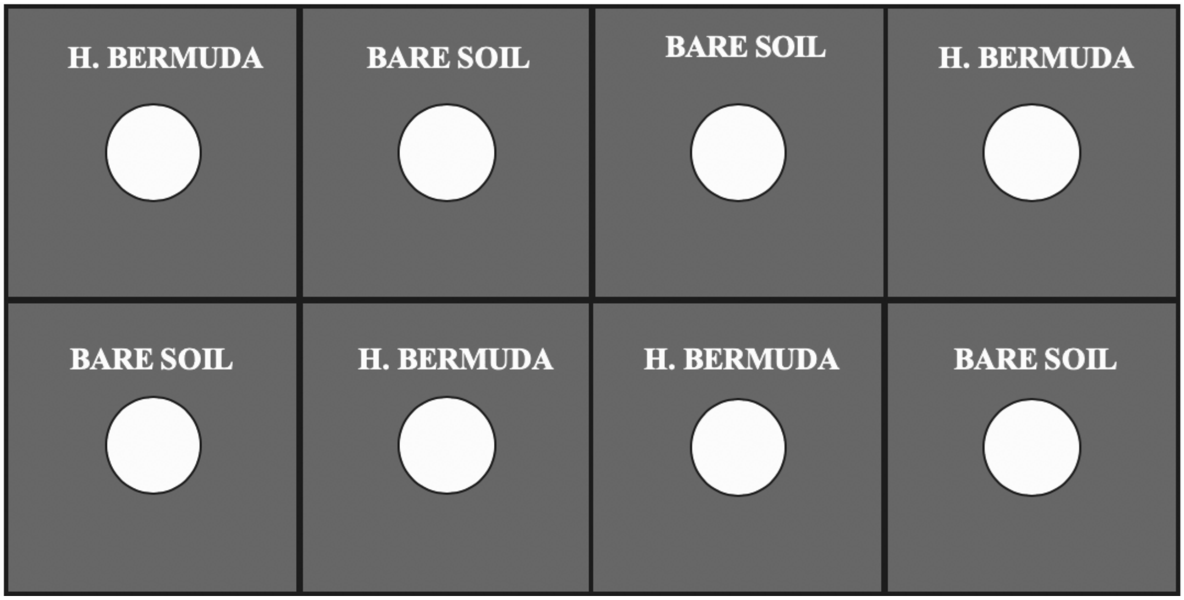

Figure 1. Arrangement of annual bluegrass *(Poa annua* L.) emergence plots at the East Tennessee AgResearch and Education Center – Plant Sciences Unit (Knoxville, TN) in 2019-2020. Plots ($1m^2$) were established as a hybrid bermudagrass (*C. dactylon* L. Pers. x *C. transvaalensis* Burtt-Davy) fairway or maintained as bare soil. Annual bluegrass emergence was monitored inside a 1000 cm^2 circle in the center of each plot (indicated by the circle).

removed using the same equipment and discarded. Each year annual bluegrass emergence was assessed on a weekly basis from January 1 through May 31, biweekly from June 1 through August 31, and weekly from September 1 to December 31.

Environmental monitoring devices (Earthstream. Mesur.io. Yanceyville, NC) were installed in each plot to collect soil temperature (5 cm depth), air temperature, soil moisture (5 cm depth), and daily light integral data on 15-minute intervals for the duration of the experiment. Meteorological data within a 20-meter radius of plots were also collected from publicly available sources including the National Oceanic & Atmospheric Administration (NOAA), the European Space Agency (ESA), and the National Climate Reference Network. According to Kirk-Davidoff et al. (2005), random errors can be reduced only by increasing the number of observations in a climate monitoring dataset beyond those captured using only a site-specific sensor. Using data from auxiliary sources along with those captured by in-ground sensors reduces the risk of point sample information not accurately representing actual variable averages such that inferences can be made about annual bluegrass across a wider scale than the immediate area around the in-ground sensor.

Auxiliary Locations

In order to expand inference beyond ETREC, data were collected at auxiliary locations during the autumn of 2020. These auxiliary locations are described below.

Lambert Acres Golf Course

Plots were established at Lambert Acres Golf Course (Alcoa, TN; 35.75 °N, -83.88 °W). Annual bluegrass emergence was monitored in bermudagrass (*Cynodon* spp.) golf course roughs with a natural history of annual bluegrass infestation. Height of cut measured 3.8 cm. Two plots (1 m x 1 m) were placed within 75 meters of each other, both at an elevation of 300 meters above sea level. Soil was an Emory silt loam (Fine-silty, siliceous, active, thermic Fluventic Humic Dystrudepts) with soil pH 5.4 and water pH 7.6. Phosphorus (Mehlich-I), potassium, calcium, and magnesium concentrations in soil measured 114, 250, 1595, and 148 ppm, respectively. Annual bluegrass emergence was monitored inside a circle (1,000 cm^2) in the center of each plot using methods previously described. Emerged weeds other than annual bluegrass were removed and discarded. Annual bluegrass emergence was assessed on a weekly basis from August through November 2020.

Three Ridges Golf Course

Plots were established at Three Ridges Golf Course (Knoxville, TN; 36.09 °N, -83.84 °W). Annual bluegrass emergence was monitored in bermudagrass (*Cynodon* spp.) golf course roughs with a natural history of annual bluegrass infestation. Height of cut measured 3.8 cm. Two plots (1 m x 1 m) were placed within 215 meters of each other, both at an elevation of 375 meters above sea level. Soil was an Urban land-Udorthents complex with soil pH 5.9 and water pH 7.7. Phosphorus (Mehlich-I), potassium, calcium, and magnesium concentrations in soil measured 17, 278, 2150, and 230 ppm, respectively. Annual bluegrass emergence was monitored inside a circle (1,000 cm^2) in the center of each plot, as described previously. Emerged weeds other than annual bluegrass were removed and discarded. Annual bluegrass emergence was assessed on a weekly basis from August through November 2020.

Model Development

Annual bluegrass emergence data were fit to non-linear functions using the Python (Python 3.8.7 python.org 2020) programming language. Several libraries were used in the model development process including ‘pandas’ for data handling (v. 1.2.0; https://pandas.pydata.org/), ‘numpy’ for numerical operations (v. 1.19.0; https://numpy.org/), ‘scikit learn’ for model building (v. 0.24; https://scikit-learn.org/stable/), ‘scipy’ for curve fitting (v. 1.5.4; https://www.scipy.org/). Model visualization was conducted using both ‘matplotlib’ (v. 3.3.3; https://matplotlib.org/3.3.3/index.html) and ‘seaborn’ (v. 0.11.1; https://seaborn.pydata.org/).

Two models were developed using annual bluegrass emergence data collected in 2019 and validated in 2020. The initial model targeted initiation of annual bluegrass emergence in autumn. Early-season emergence data (0 to 50% yearly total) and cooling degree day accumulation date were fit to a Gompertz function (Eq. 1). Cooling degree days (CDD_{21C}) were calculated using a 21°C base temperature with accumulation totaled after June 21st each year.

$$ESE = a * e^{-b*e^{\wedge}-c*CDD21C} \qquad [Eq. 1]$$

In this Gompertz function, ESE = early-season emergence (%), a, b, and c are regression coefficients, and CDD_{21C} = cooling degree days accumulated from the summer solstice using a 21°C base temperature. This model was developed using data collected from ETREC in 2019 and validated at three locations in 2020: ETREC, Lambert Acres Golf Course, and Three Ridges Golf Course.

A second model was developed to better understand the entirety of annual bluegrass emergence throughout autumn. Yearly cumulative emergence (YCE) data were regressed against CDD_{21C} accumulation and fit to a ruminal degradation curve (Eq. 2).

$$YCE = -a + b * (1- e^{-c*CDD21C}) \qquad [Eq. 2]$$

In this function, YCE = yearly cumulative annual bluegrass emergence (%), a, b, and c are regression coefficients, and CDD_{21C} = cooling degree days accumulated from the summer solstice using a 21°C base temperature. This model was developed using data collected from ETREC in 2019 and validated using data collected there in 2020. In all cases, model fit was determined using three parameters: coefficient of determination (R^2), mean absolute error

(MAE), and mean squared log error (MSLE). MAE provided an assessment of error between paired observations expressing the same phenomenon (Sammut 2011a), while MSLE measures the average of the squares of these errors (Sammut 2011b). All statistical analyses are available in a Google collaborative environment at: https://colab.research.google.com/drive/1wUfWjBMR28VOM8I_hi7OeVq2m6e5w8bG?usp=sharing.

Section III
Results and Discussions

Early Season Emergence Model

A Gompertz function fit early-season annual bluegrass emergence data collected at ETREC well in 2019 (Table 1. Figure 2). However, MAE and MSLE values for this model increased in 2020 at ETREC and the auxiliary locations. Moreover, R^2 values were markedly lower in 2020 compared to 2019. For example, using data collected at ETREC, the R^2 value for this model measured 0.73 in 2019 compared 0.71 in 2020; values for the auxiliary locations in 2020 were ≤ 0.31 suggesting that this model fit emergence data at these sites worse than ETREC.

At ETREC in 2019, annual bluegrass emergence was documented when 12 CDD_{21C} accumulated (September 4). In 2020, initial emergence was documented at ETREC when 8 CDD_{21C} accumulated (August 5), almost a full month earlier than 2019. Earlier annual bluegrass emergence timing could be related to cooler air temperature as monthly averages were lower in 2020 for both August (24.9°C versus 25.8°C) and September (21.2°C versus 25.8°C). Air temperatures where annual bluegrass emergence was initially observed each year were within the 10 to 39°C range reported by McElroy et al. (2004). However, it should be noted that air temperature might not be the best predictor given that emergence was not documented at either auxiliary location in 2020 until 72 CDD_{21C} accumulated on October 1 (Figure 2). This discrepancy in emergence timing between ETREC and the auxiliary locations may be related to soil moisture considering that plots at the auxiliary locations were irrigated only via rainfall whereas those at ETREC received both rainfall and supplemental irrigation. Peachey (2001) reported that annual bluegrass emerges following rainfall events in late summer or early fall.

Emergence of annual bluegrass occurred two days after sites received 78.6 to 87.7 mm rainfall in a six-day period.

Table 1. Gompertz function to fit early season (0 to 50% yearly maximum) annual bluegrass (*Poa annua* L.) emergence data collected at the East Tennessee AgResearch and Education Center – Plant Sciences Unit (ETREC; Knoxville, TN) in 2019 and 2020, as well as Lambert Acres Golf Course (Alcoa, TN) and Three Ridges Golf Course (Knoxville, TN) in 2020. Annual bluegrass emergence was monitored in plots (1 m^2) established as a hybrid bermudagrass (*C. dactylon* L. Pers. x *C. transvaalensis* Burtt-Davy) on a weekly basis.

Year[a]	Location	R^{2b}	MAE	MSLE
2019	ETREC	0.74	0.014	0.00081
2020	ETREC	0.71	0.021	0.00118
	Three Ridges	0.26	0.037	0.00210
	Lambert Acres	0.31	0.026	0.00145
	All locations combined	0.53	0.027	0.00154

[a] Early season annual bluegrass emergence data and cooling degree days (CDD_{21C}) accumulation data were fit to the following Gompertz function each year: Emergence (%) = 0.485 * exp (-12.141* exp(-0.081* CDD_{21C}))

[b] Model fit was assessed using coefficient of determination (R^2), mean absolute error (MAE), and mean squared log error.

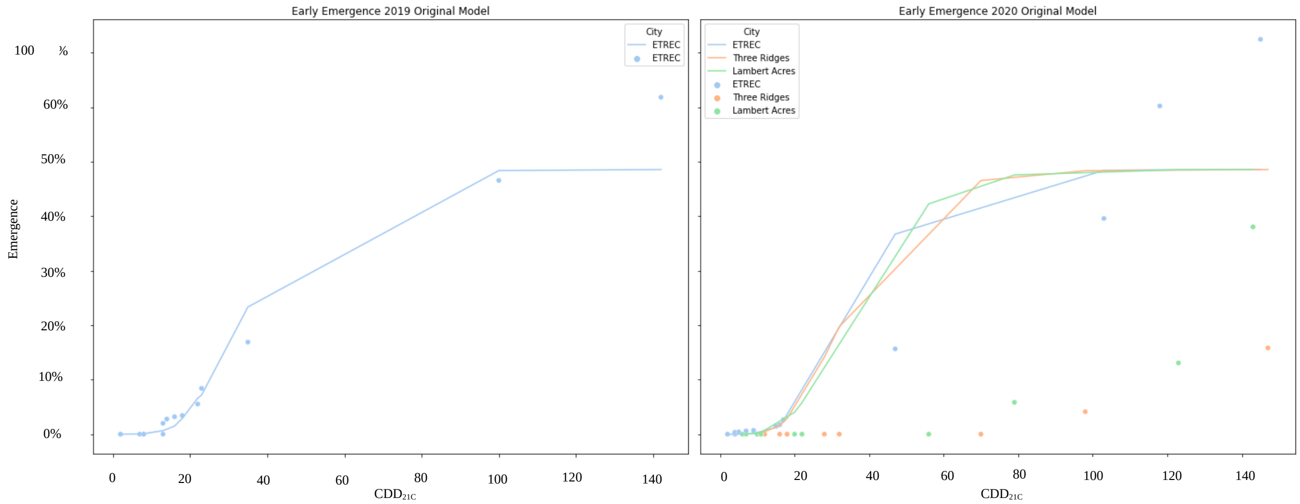

Figure 2. Gompertz function fit to early season (0 to 50% yearly maximum) annual bluegrass (*Poa annua* L.) emergence data collected at the East Tennessee AgResearch and Education Center – Plant Sciences Unit (Knoxville, TN) in 2019 and 2020, as well as Lambert Acres Golf Course (Alcoa, TN) and Three Ridges Golf Course (Knoxville, TN) in 2020. Annual bluegrass emergence data were collected weekly with observations were regressed over cooling degree days (CDD_{21C}) with accumulation beginning at the summer solstice using a 21°C base temperature. Colored circles represent actual observations whereas the solid line represents model predictions. Measures of model fit for each location and year are presented in Table 1.

Yearly Cumulative Emergence Model

A ruminal degradation curve fit yearly cumulative annual bluegrass emergence data collected at ETREC well in 2019 (Table 2. Figure 3). However, MAE and MSLE values for this model increased in 2020 and the coefficient of determination decreased (Table 2). Despite the increases in overall MAE and MSLE values, findings illustrate that CDD_{21C} accumulation accounted for over 82% of the variation in annual bluegrass emergence at the ETREC location over a two-year period.

In 2019, annual bluegrass emergence was first documented at ETREC when 12 CDD_{21C} accumulated and continued throughout autumn. Emergence measured 50% by the time 141 CDD_{21C} had accumulated (October 27), and reached 75% emergence by the time 288 CDD_{21C} accumulated (November 9). Using 2019 total plant count data, peak (61% of the yearly total) emergence occurred during the 4-week period between October 11 and November 3, which corresponded to 32 to 211 CDD_{21C}. Average day/night air temperatures during this period were 20.3/8.2°C, respectively, whereas soil temperature averaged 16.6°C. These observations in 2019 align with findings of Kaminski and Dernoeden (2007) who recorded peak annual bluegrass emergence in cool-season turfgrass roughs on golf courses once air temperatures fell to 20°C. Additionally, McElroy et al. (2004) reported that the optimal air temperature for annual bluegrass germination was 19°C during the day and 10°C during the evening. Conversely, data from 2019 do not align with those reported by Callahan and McDonald (1992) who observed annual bluegrass emergence in a creeping bentgrass putting green from November to January in Tennessee. A reason for this difference may be that data in this study were collected from a golf courses fairway established on silty clay soil compared to the sand-based rootzones often used on putting greens.

Table 2. Ruminal degradation curve fit to full season annual bluegrass (*Poa annua* L.) emergence data collected at East Tennessee AgResearch and Education Center – Plant Sciences Unit (ETREC) (Knoxville, TN) in 2019 and 2020. Annual bluegrass emergence was monitored on a weekly basis in plots (1 m^2) established as a hybrid bermudagrass (*C. dactylon* L. Pers. x *C. transvaalensis* Burtt-Davy) fairway and maintained as bare soil.

Year[a]	R^2[b]	MAE	MSLE
2019	0.95	0.062	0.0031
2020	0.82	0.119	0.0111

[a] Yearly cumulative annual bluegrass emergence data and cooling degree days (CDD_{21C}) accumulation data were fit to the following ruminal degradation function: Emergence (%) = - 0.01275 + 0.9220 + (1-exp(-0.004 x CDD_{21C}))

[b] Model fit was assessed using coefficient of determination (R^2), mean absolute error (MAE), and mean squared log error.

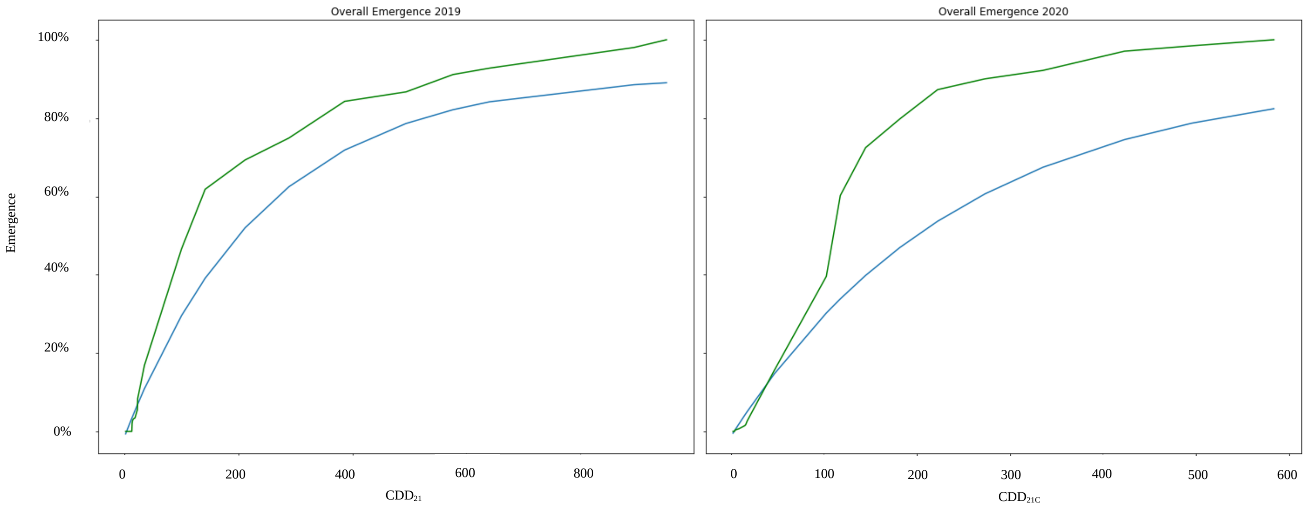

Figure 3. Four-parameter ruminal degradation curve to fit yearly cumulative annual bluegrass (*Poa annua* L.) emergence data collected at East Tennessee AgResearch and Education Center – Plant Sciences Unit (Knoxville, TN) in 2019 and 2020. Annual bluegrass emergence was monitored on a weekly basis in plots (1 m^2) established as a hybrid bermudagrass (*C. dactylon* L. Pers. x *C. transvaalensis* Burtt-Davy) fairway and maintained as bare soil. Combined observations were regressed over cooling degree day accumulation from the summer solstice using a 21°C base temperature (CDD_{21C}). The blue line represents model predictions whereas the green line represents actual observations each year. Measures of model fit for each year are presented in Table 2.

In 2020, annual bluegrass emergence was first documented at ETREC after 8 CDD_{21C} accumulated on August 5th and continued throughout autumn. Annual bluegrass emergence in 2020 reached 50% and 75% by the time 117 CDD_{21C} (October 9) and 188 CDD_{21C} accumulated (October 22nd), respectively. Peak annual bluegrass emergence (61% of yearly total) occurred during the four-week period between September 24 and October 16, which corresponded to 46 to 145 CDD_{21C}. Average day/night air temperatures during this period were 22.7/11.2°C, respectively, whereas soil temperatures averaged 18.9°C. This period of peak emergence at ETREC occurred earlier in 2020 than 2019 and air temperature alone does not explain this difference considering that day/night air temperature averages during this four-week period were higher in 2020 than 2019. Interestingly, there were substantial differences in rainfall between years that may explain the shift in the period of peak emergence. In 2019, rainfall totaled 139.7 mm for the months September and October, respectively, compared to 226.6 mm in 2020.

The yearly cumulative emergence model developed using 2019 data collected at ETREC underpredicted emergence in 2020 (Figure 3). For example, this model suggested that 50% and 75% annual bluegrass emergence would occur at 225 and 445 CDD_{21C}, respectively. In 2020, these benchmark targets were met at 117 and 181 CDD_{21C}, respectively. Increased soil moisture may have influenced annual bluegrass emergence in 2020. Although this site received irrigation to supplement rainfall, there was an 87 mm difference in rainfall accumulation during September-October 2020 compared to 2019. Further, CDD_{21C} only accounted for 82% of the variability in emergence data collected in 2020 compared to 95% in 2019 (Table 2). This difference in rainfall over years may explain this change and suggests that future models incorporate both parameters.

Overall annual bluegrass emergence at ETREC in 2020 was less than 2019, suggesting that the seedbank in experimental plots may have been depleted by physically removing emerged seedlings with tweezers after counting. When summing over plots at ETREC monitored over two-years, 2,050 annual bluegrass seedlings emerged in 2019 compared to 1,334 in 2020. Interestingly, minimal emergence (< 10%) was noted in spring of either year. A reduction of viable seed is a key component to any weed management program. According to Norsworthy et al. (2012), soil seedbank management is a best management practice for resistance that can be accomplished via both physical and chemical control. Brosnan et al. (2020) evaluated physical weed control of annual bluegrass in zoysiagrass (*Zoysia* spp. (L.) Merr.) by fraise mowing. Researchers reported fraise mowing removal resulted in a 24% reduction in annual bluegrass cover the following spring but did not observe a difference in the quantity of annual bluegrass seed in the seedbanks of fraise-mowed and non-treated plots. Preemergence herbicides from several groups (e.g., Group 3, 14, 29) can be used to effectively control annual bluegrass by acting within the soil seedbank. Coupling mechanical techniques with optimally timed chemical control options could offer an integrated strategy for depleting the annual bluegrass seedbank in soil.

Section IV
Conclusion

Results of this two-year study facilitated a better understanding of environmental factors affecting annual bluegrass emergence from soil. Overall, fluctuations in CDD_{21C} accounted for ≥ 82% of the variance in yearly cumulative annual bluegrass emergence data in an irrigated hybrid bermudagrass fairway at ETREC. While non-linear models were able to fit both early-season and yearly cumulative annual bluegrass emergence data post-hoc in 2019, they were not able to accurately predict the same phenomenon in 2020. Although annual bluegrass emergence was first noted at a similar CDD_{21C} benchmark each year (12 CDD_{21C} in 2019 and 8 CDD_{21C} in 2020), the yearly cumulative emergence model did not accurately predict when 50 and 75% emergence benchmarks would occur in 2020. Additional research is needed to better understand environmental benchmarks associated with 50% yearly cumulative emergence considering that it represents an optimal time to apply a mixture of pre- and postemergence herbicide to control annual bluegrass, which can mitigate the evolution of resistance (Busi et al. 2020). Future research should also be conducted using the 24-month dataset generated in this research to develop new annual bluegrass emergence models for validation over a wide geographic range. An iterative process of model development and validation could lead to turfgrass managers having a reliable tool to assist with timing measures for annual bluegrass control.

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Appendix

Annual bluegrass emergence data collected during the 24-month period of January 2019 through December 2020 were used to generate a non-linear model to predict yearly annual bluegrass emergence patterns in bermudagrass (*Cynodon* spp.) This new model was then fit to the 2019 and 2020 data sets generated in this research using previously described statistical procedures. Results are presented below to demonstrate improvements in model fit in each year. A four-parameter exponential function to predict yearly cumulative annual bluegrass emergence using a 24-month dataset and presented below in Equation 3.

$$\text{Emergence (\%)} = 0.939 * \exp(-4.655 * \exp(-0.0125 * CDD_{21C})) \quad [3]$$

Table A1. Improvements in model fit when using a ruminal degradation curve generated using a 24-month dataset to describe annual bluegrass (*Poa annua* L.) emergence in a hybrid bermudagrass (*C. dactylon* L. Pers. *x C. transvaalensis* Burtt-Davy) golf course fairway at the East Tennessee AgResearch and Education Center-Plant Sciences Unit in Knoxville, TN during 2019 and 2020.

Year	Previous R^2	New R^2	Previous MAE	New MAE	Previous MSLE	New MSLE
2019	0.95	0.97	0.062	0.045	0.0031	0.0026
2020	0.82	0.92	0.119	0.072	0.0111	0.0054

[a] Full season annual bluegrass emergence data and cooling degree days (CDD_{21C}) accumulation data were fit to the following ruminal degradation function: Emergence (%) = 0.939 * exp(-4.655* exp(-0.0125 * CDD_{21C}))

[b] Model fit was assessed using coefficient of determination (R^2), mean absolute error (MAE), and mean squared log error.

Vita

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