Measuring the Effect of Different Grass Types on PGA Tour Putting Performance

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Introduction

Golf is a sport that dates back to at least the 15th century in Scotland, and there are claims that its origins could be earlier still. [1] The objective of golf is to move a small ball from a starting position (the "tee") into a hole some distance away (typically between 100 and 600 yards) in as few strokes as possible, using a set of 14 clubs. The number of strokes taken is recorded as the player's score for that hole, and a round will typically comprise 9 or 18 of such holes.

Professional golf is played via a number of tours throughout the world. The most prestigious of these tours in men's golf is the PGA Tour, primarily based in the USA, whose formal origins date to 1968. [2] The format of most PGA Tour tournaments is 72 hole strokeplay. Players complete four 18-hole rounds, with the lowest cumulative total deciding the winner. A cut is usually made after two rounds, whereby only the top 65 players (including ties) are allowed to advance to the final two rounds. Ties for first place at the conclusion of 72 holes are decided via a playoff between the two or more competitors who share the lowest score.

A particularly distinct phase of the game is putting, which involves rolling the ball along a closely mown area of grass known as the green, with the aim of getting the ball close to, and ultimately into, the hole. The subject of putting has been subject to academic study since the 1960s. [3] Putting draws particular interest because of its combination of skill and psychological elements, as well as the high-leverage moments of drama surrounding famous putts. [4] Many different techniques have been utilized for putting at the professional level. These include different length putters (the longest putters are sometimes known as 'broomsticks') and a variety of grip methods such as the claw, cross-handed, or the arm-lock. Different grip methods have been shown to affect a golfer's head and eye movement. [5] Sometimes a player will try a new putting technique after suffering an attack of the 'yips' – a psychological condition whereby a player loses control of his/her fine motor skills and may experience sudden spasmic movements when finesse is required. [6]

Statistical measures of putting performance have developed over time. Early analysis used raw metrics such as the total putts per round. [7] However, this is obviously biased and a crude measure of putting success as it is affected by the starting position of the ball on each green – if a player chips the ball from just off the green to a distance of six inches from the hole, then they will almost certainly take only one putt on the hole, but that is reflective of the player's chipping skill rather than their skill with the putter. Slightly more advanced analysis used a statistic called *putting average*, which measures the average number of putts only when a green is hit in the regulation number of strokes. [8] Compared to using total putts, *putting average* reduces bias by ignoring holes where a player misses the green and then plays a chip shot, which typically will leave a much shorter putt than an approach shot played from 100 yards or more. However, it still cannot account for the fact that some approach shots end up closer to the hole than others, leaving easier putts.

Beginning in 2004, the PGA Tour began implementing its ShotLink system which utilized on-course volunteers to record the precise location of every stroke. This allowed for more advanced analysis of the game, and Mark Broadie developed the *strokes gained* methodology that is now the most common reference for putting performance. [9] The formula to calculate *strokes gained* on a single green is to subtract the actual number of putts taken from the expected number of putts a PGA Tour professional would take from that distance. A simple example would be to consider a putt that professionals are

expected to hole 50% of the time and miss 50% of the time, which Broadie and others have shown to be around 8 feet. [9] If we temporarily ignore the probability of taking 3 or more putts from this distance, since that is rare on the PGA Tour, this means that the expected number of putts is (2 + 1) / 2 = 1.5. Therefore, if the player holes the putt, they have gained 1.5 – 1 = 0.5 strokes, while if the player misses the putt (assuming they then hole the next putt) they have gained 1.5 – 2 = -0.5 strokes (i.e. 0.5 strokes 'lost'). Summing these scores for each hole can give an indication of a player's putting performance over a round, a tournament, a season, or a player's entire career. In a subsequent paper, Broadie found that putting explains around 17 per cent of variance in scores in the PGA Tour from 2003 to 2010. [10]

Although the objective of every putt is ostensibly to roll the ball into the hole, this becomes less likely at longer distances. As the distance of the putt increases, the primary objective shifts from holing the putt to leaving the ball as close as possible to the hole in order that the subsequent putt can be holed. This act of trying to get longer putts close to the hole is known as lag putting. Lag putts can also be judged using the *strokes gained* methodology, since there is an expected number of putts attached to any starting distance. For example, if a player's ball begins at a position where they are expected to take 2.2 putts to hole out, and their first putt ends 8 feet from the hole, then we know from the previous example that they are now expected to take 1.5 putts from the new position. Including the stroke they have just taken, that means the player's *strokes gained* for the first putt was 2.2 – 1 – 1.5 = -0.3 (i.e. 0.3 strokes 'lost'). If the subsequent 8-foot putt is holed then the net *strokes gained* for the hole would improve to 0.2, but this would not fully explain the breakdown of the two strokes played (a poor lag putt followed by a good short putt).

The physics of putting involve an attempt to strike the ball with the putter along a particular starting direction along with a matching pace that gives the ball the maximum chance of dropping in the hole, while leaving an easy follow-up putt in the event the first putt misses. Even before the putt is struck, assessing the correct line and speed is a particularly important skill. According to Karlsen and Nilsson, as much as 60% of distance variability in putting results from accurately reading the green conditions. [11] After the ball is struck, it begins a sliding phase followed by a rolling phase. There are several factors that can affect the difficulty of a putt. Most obviously, the starting position of the ball - it can be assumed that longer putts are generally more difficult to hole than shorter putts. Additionally, there are factors relating to the condition of the green: the speed of the green and the amount of slope, as well as different types of grass. On the PGA Tour, the three predominant grasses used on putting surfaces are Bermuda, Bentgrass, and *Poa annua*. Different grasses are favored in different parts of the United States based on the local climate. In particular, *Poa annua* is known as a difficult grass to putt on. An annual bluegrass, *Poa annua* is considered an invasive weed that grows unevenly and produces prominent seed heads. [12]

Weather factors include wind, which can not only blow the ball itself but also affect the balance of the player, and rain which can cause a small amount of surface water on the green (although tournaments are usually delayed if this becomes excessive). There are knowledge factors, such as when the player gains an advantage by watching the speed and slope of the green from a prior putt by himself or a playing partner. [13] There are also various psychological factors. Hickman and Metz found that as the monetary value of a putt increases, the likelihood of holing the putt decreases. [14] Players who are close to the lead before the start of the final round have been found to perform worse than usual. [15] And finally, Pope and Schweitzer found that golfers are subject to 'loss aversion' behavior and are more likely to hole a putt for par than a putt for birdie from the same location. [13]

Statement of Aims

Using a dataset of shots from the PGA Tour and ShotLink, four research questions were addressed:

1. Is there a relationship between different grass types and putting performance?

2. Does the category of the previous shot (putt, chip, or full shot) affect the chance of a putt being holed? If so, does this effect vary across different surfaces?

3. How do putts on *Poa annua* greens compare to other surfaces at different starting distances?

4. Do the best putters tend to perform better or worse on *Poa annua*, relative to other players?

Data & Methods

Data Description

Data was collected from the PGA Tour's public API during the years 2015 to 2017. Data was downloaded at the conclusion of each day's play and includes a total of 1,897,009 observations (i.e. strokes).

The dataset includes 10 variables as follows:

- Player – The name of the player.
- Hole – The number of the hole.
- Stroke – The number of the stroke on that particular hole.
- Start Lie – The type of lie on which the ball started.
- Distance – The distance (in yards) that the ball traveled before coming to rest.
- End Lie – The type of lie on which the ball came to rest.
- End Distance – The distance (in yards) between where the ball came to rest and the hole.
- Holed – Whether the shot was holed.
- Putt – The number of the putt taken on this hole (if applicable).
- Description – A text description of the stroke, including the stroke number, distance traveled, end lie and end distance (the last two variables are replaced by "in the hole" if the shot was holed).

Additionally, 4 new variables were derived from the original variables above. Those variables are:

- Start Distance – The End Distance of the previous shot.
- Prev Shot Distance – The Distance (traveled) of the previous shot.
- Prev Shot Lie – The Start Lie of the previous shot.
- Num Putts – The total number of putts taken on the hole.

Some basic data cleaning was performed, including identifying and removing duplicate entries. There were some putts with a start distance of zero; these were found to be from PGA Tour rounds where ShotLink was not in operation. Often this is when an event is played over multiple courses, but for logistical reasons the PGA Tour only operates ShotLink at a single course. There was also an event (the

2015 AT&T Byron Nelson) where ShotLink was not in operation due to inclement weather. These values were not included in the analysis.

There were also 124 instances where a player hit a first putt but did not finish the hole. Many of these were from the Barracuda Championship which operates an alternative "Stableford" scoring system that has a maximum score for each hole, meaning a player can simply give up and move to the next hole once he has reached the maximum number of strokes. Given the alternative format of this event, the Barracuda Championship was removed from the dataset.

Furthermore, it was identified that for many of the 2nd round shots in the database, only the players who made the cut were included. This is because the PGA Tour API removes players who miss the cut shortly after the second round has concluded, and so these players can be missed if data collection is not performed quickly enough. This created a potential bias in the second round data, and data from such rounds was excluded from the analysis.

Following the data cleaning, there were a total of 1,432,917 shots in the dataset, of which 547,522 were putts. The categorization of putts into first putt, second putt, and so on are shown in Table 1.

Table 1. Frequency of the ordinal rank of putts in the dataset.

Putt Number	Frequency	Rel. Frequency
1	335324	61.2%
2	202320	37.0%
3	9731	1.8%
4	138	0.03%
5	9	0.002%

Data relating to the type of grass used on the greens at PGA Tour events were kindly provided by the Golf Course Superintendents Association of America. These were grouped into four categories: Bermuda, Bentgrass, Bentgrass/Poa mix, and *Poa annua*. Plotting the category of each course onto a map of the United States reveals the relationship between grass choice and climate. Bermuda grass is preferred in hot climates such as the South, the deserts of the Southwest, and Hawaii. Bentgrass and *Poa annua* are found in cooler areas with less sunlight.

Figure 1. Grass types of PGA Tour events in 2015-16 and 2016-17 seasons.

Statistics for player putting skill were compiled from the PGA Tour's ranking of Strokes Gained Putting for seasons 2015/16 and 2016/17, with the two tables combined into a two-year average for each player. The best-performing putter over the two seasons was Jason Day at +0.739 strokes gained per round, while the worst was Greg Owen at -0.987.

Table 2. Top 5 players on PGA Tour by mean *Strokes Gained Putting* across 2015-16 and 2016-17 seasons.

Player	Total SGP	Measured Rounds	Mean SGP
Jason Day	80.54	109	0.739
Andrew Landry	21.59	33	0.654
Steve Stricker	27.90	45	0.620
Jonas Blixt	67.44	127	0.531
Brian Harman	94.36	178	0.530

Table 3. Bottom 5 players on PGA Tour by mean *Strokes Gained Putting* across 2015-16 and 2016-17 seasons.

Player	Total SGP	Measured Rounds	Mean SGP
Derek Ernst	-23.91	43	-0.556
Boo Weekley	-74.14	132	-0.562
Brad Fritsch	-25.05	42	-0.596
Rory Sabbatini	-55.75	92	-0.606
Greg Owen	-68.14	69	-0.987

Statistical Methods

To allocate a measure of performance to any putt, it is first necessary to assess an expected performance. To this end, a model was created to calculate an *expected putts* value from any starting position on a green. Figure 2 shows the mean actual number of putts taken as starting distance increases, having a nonlinear, somewhat sigmoidal shaped distribution. Distances in this graph are

rounded to the nearest foot. At higher distances where sample sizes are smaller, the data become scattered.

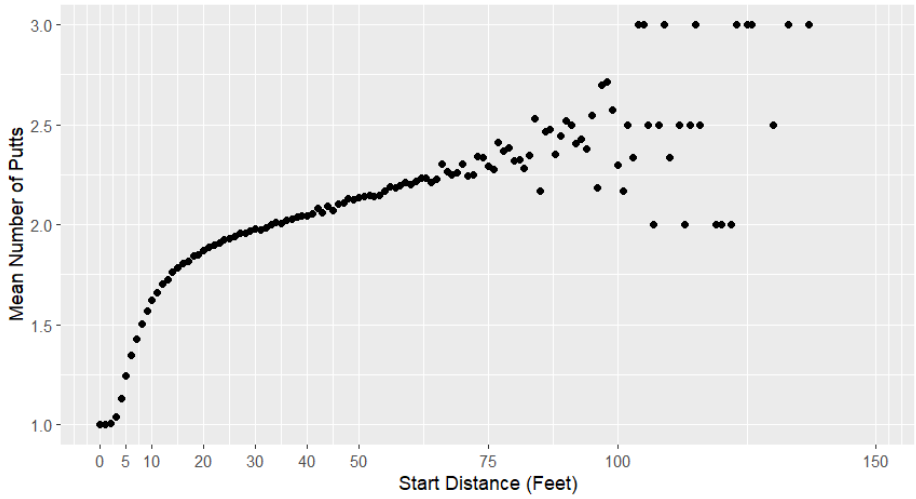

Figure 2. Mean number of putts by starting distance, rounded to nearest foot.

Similar to the approach of Fearing et al., separate models were created to estimate the probability of taking one, three, or four putts as a function of starting distance. [16] Two putts would then act as the default, with the probability of five or more putts being sufficiently small on the PGA Tour (0.000027%) that it was decided this eventuality could be ignored without significantly affecting the model.

Given the probabilities of one, two, three, and four putts, the expected number of putts can be calculated using the expected value formula

$$E(X) = \sum_{x} x_i p_i$$

which in this case is

$$E(putts) = \sum_{i=1}^{4} x_i p_i$$

where $p_2 = 1 - (p_1 + p_3 + p_4)$.

Using this model, an *expected putts* value could be derived for every starting position on every green. By comparing *expected putts* with the actual number of putts taken (*num putts*), the variable *putts difference* was created with the formula:

$$putts\ difference\ =\ num\ putts\ -\ expected\ putts.$$

For the first research question, the mean *putts difference* was compared across each of the four categories of greens (Bermuda, Bentgrass, Bentgrass/Poa mix, *Poa annua*) using a one-way ANOVA test. A post-hoc Tukey test was used to assess pairwise differences between grass types.

For the second research question, to measure the effect of the previous shot (putt, short shot, or full shot) on putting performance, it was decided to only use putts of 15 feet or less. This is because almost

all putts that follow another putt will be within this range, whereas putts that follow a long shot will often be from longer distances. Using only putts of 15 feet or less would give a like-for-like comparison. Additionally, putts from less than 3 feet were ignored, because many of these putts were 'tap-ins' that would be made 100% of the time. Short game shots were deemed to be shots from 90 feet or less, while full shots were from 80 yards (240 feet) or more.

Means were calculated for each of the three previous shot categories, and a one-way ANOVA test was performed, along with a post-hoc Tukey test. The means were then calculated using only *Poa annua* greens for comparison, and a two-way ANOVA test was performed to look for interactions between grass type and the previous shot category. Estimated marginal means were plotted using R's `emmeans` function.

For the third research question, putts from difference distances were compared by their *putts difference*. However, one problem with this method is that it does not account for the quality of each putt. A good first putt that ends 6 inches from the hole and is then tapped in would be counted the same as a poor first putt that ends up 10 feet from the hole but is then holed with a good second putt.

To account for this, a *strokes gained* variable was created for each putt. This required calculating *expected putts* from the end position of the putt (zero if the putt was holed) and using the formula

$$strokesgained = expectedputts(start) - expectedputts(end) - 1.$$

Both *putts difference* and *strokes gained* were graphed against the starting distance of the putt. To test for an interaction between distance and *Poa annua* greens, a binary variable called *poa* was added denoting whether or not the grass was *Poa annua*, and a simple linear models were created to predict first *putts difference*, then *strokes gained* using starting distance, *poa*, and the interaction between the two variables.

For the final research question, players were divided into quartiles based on their cumulative *strokes gained putting* (SGP) over the two seasons being analyzed. Performance of players in each quartile on *Poa annua* was compared with their performance on greens with no *Poa annua* (i.e. Bentgrass or Bermuda). Finally, a two-way ANOVA test was performed using grass type and SGP quartile to predict *putts difference*, and estimated marginal means were plotted.

Results

For the one-putt and three-putt models it was found that a model including the natural log of the starting distance as well as a 4^{th}-order polynomial was a good fit for the data.

Table 4. Results of the logistic regression for the probability of taking one putt to hole out from the starting location.

```
Coefficients:
                    Estimate Std. Error z value Pr(>|z|)
(Intercept)         7.650e+00  4.693e-02  163.01   <2e-16 ***
log(Start.Distance) -6.164e+00  8.574e-02  -71.89   <2e-16 ***
Start.Distance       8.116e-01  2.361e-02   34.38   <2e-16 ***
sd2                 -2.434e-02  9.614e-04  -25.31   <2e-16 ***
sd3                  3.679e-04  1.886e-05   19.50   <2e-16 ***
sd4                 -2.053e-06  1.320e-07  -15.55   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 731107  on 547521  degrees of freedom
Residual deviance: 316217  on 547516  degrees of freedom
AIC: 316229
```

Coefficients can be seen to be statistically significant for all variables. This results in the following formula for the log odds of a putt being holed from some starting distance d:

$$log\left(\frac{P(oneputt)}{1-P(oneputt)}\right) = 7.65 - 6.164log(d) + 0.812d - 0.0243d^2 + 0.000368d^3 - 0.00000205d^4.$$

When this function is plotted alongside the actual percentage of putts holed at each distance (rounded to one yard), the function fits the data well, as shown in Figure 3.

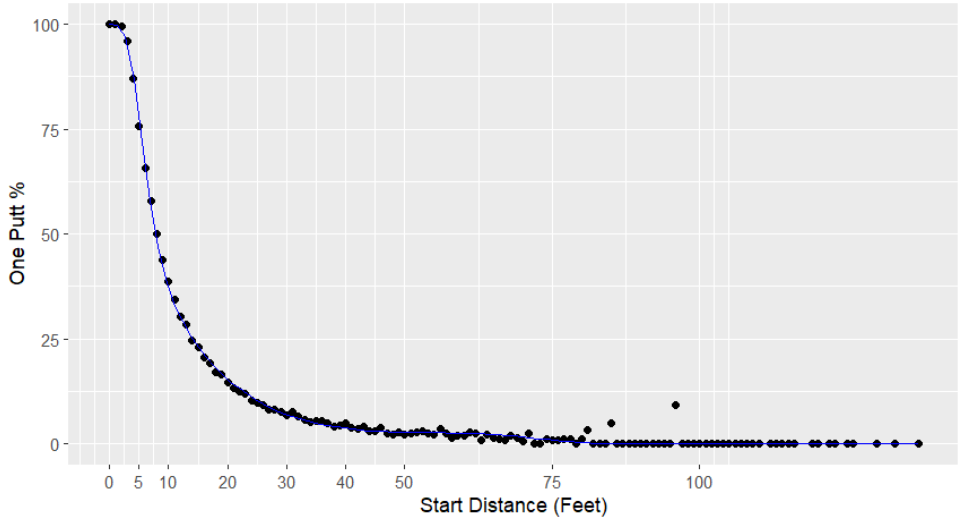

Figure 3. One-putt model (blue line) compared with actual mean one putt % (black dots).

In the three-putt logistic regression, again all variables were statistically significant.

Table 5. Results of the logistic regression for the probability of taking three putts to hole out from the starting location.

```
Coefficients:
                    Estimate Std. Error z value Pr(>|z|)
(Intercept)        -9.189e+00  1.752e-01 -52.444  < 2e-16 ***
log(Start.Distance) 2.233e+00  1.706e-01  13.092  < 2e-16 ***
Start.Distance     -1.405e-01  2.874e-02  -4.889 1.01e-06 ***
sd2                 4.397e-03  6.895e-04   6.378 1.79e-10 ***
sd3                -5.210e-05  8.061e-06  -6.463 1.03e-10 ***
sd4                 2.073e-07  3.436e-08   6.034 1.60e-09 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 97746  on 547521  degrees of freedom
Residual deviance: 70127  on 547516  degrees of freedom
AIC: 70139
```

The resulting equation to calculate the probability of a three putt based on starting distance d is as follows:

$$log\left(\frac{P(threeputt)}{1-P(threeputt)}\right) = -9.189 + 2.233log(d) - 0.1405d + 0.0044d^2 - 0.000052d^3 + 0.0000002d^4$$

Again, the model appears to be a good fit for the data (Figure 4).

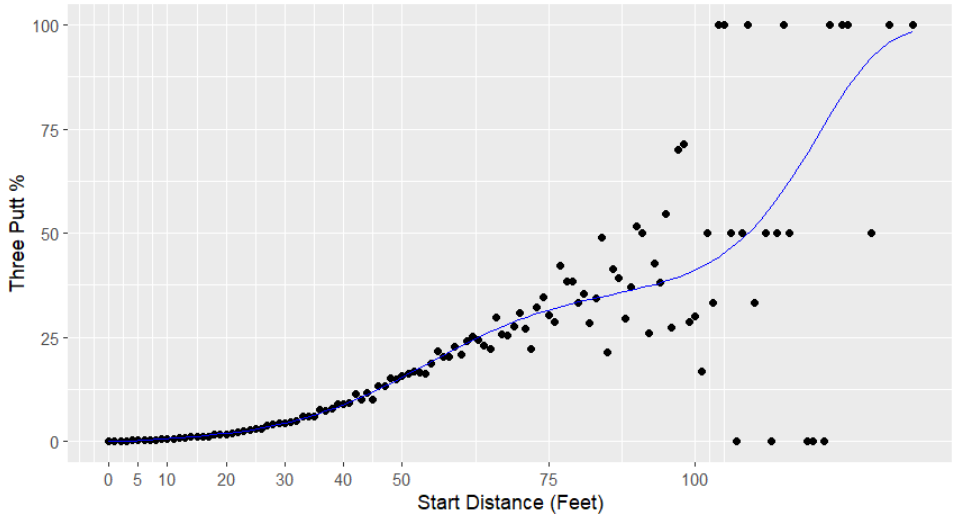

Figure 4. Three-putt model (blue line) compared with actual mean three putt % (black dots).

Meanwhile, for the four-putt model, a model with only the distance d and log distance was sufficient.

Table 6. Results of the logistic regression for the probability of taking four putts to hole out from the starting location.

```
Coefficients:
                    Estimate Std. Error z value Pr(>|z|)
(Intercept)       -11.082656   0.446220 -24.837  < 2e-16 ***
log(Start.Distance)   0.758910   0.196786   3.857 0.000115 ***
Start.Distance        0.034381   0.007496   4.587  4.5e-06 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 2562.9  on 547521  degrees of freedom
Residual deviance: 2253.7  on 547519  degrees of freedom
AIC: 2259.7
```

$$log\left(\frac{P(fourputt)}{1-P(fourputt)}\right) = -11.083 + 0.759\ log(d) + 0.034d$$

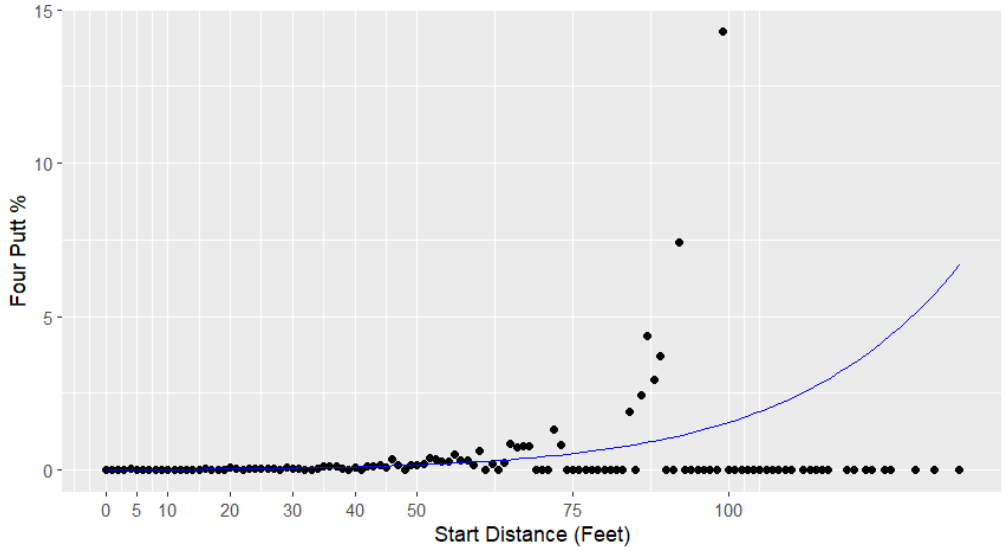

Figure 5. Four-putt model (blue line) compared with actual mean four putt % (black dots).

The final model can be shown to fit the data well (Figure 6), although it may not be reliable at longer distances, especially over 100 feet. However, it should be noted that only 0.000095% of putts in the dataset were from more than 100 feet.

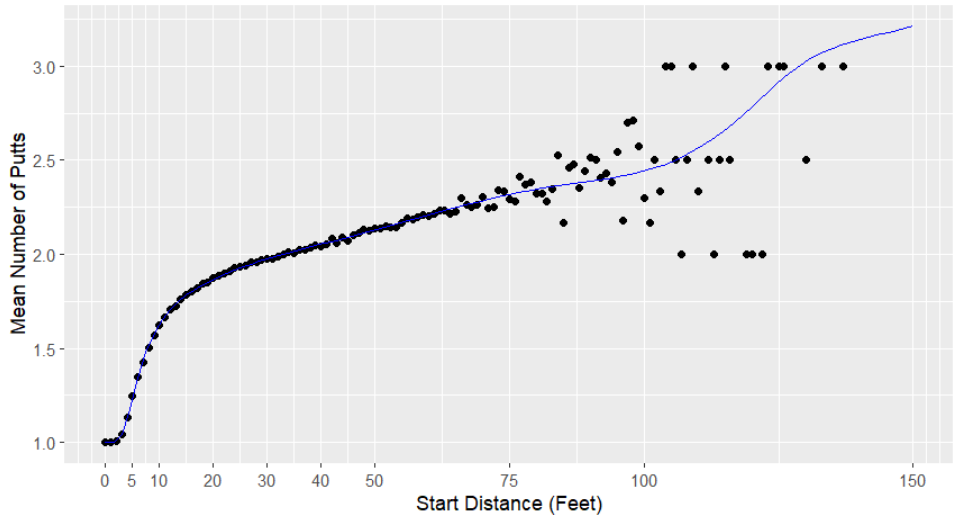

Figure 6. Final expected putts model (blue line) compared with actual mean number of putts (black dots).

RQ1. Is there a relationship between different grass types and putting performance?

Poa annua greens had a mean *putts difference* of 0.0332, higher than any other category. There was sufficient evidence in the ANOVA test (Table 8) to reject the null hypothesis that means are equal among all grass types, and the Tukey test (Figure 8) showed significant differences between all pairs of categories except for Bermuda and Bentgrass.

Table 7. Mean putts difference by grass type, with 95% confidence intervals.

Grass Type	n	Mean Putts Difference	Standard Error	95% CI
Bentgrass	81171	-0.0041	0.0014	(-0.0069, -0.0014)
Bermuda	167156	-0.0009	0.0010	(-0.0028, 0.0010)
Bentgrass/Poa mix	43289	0.0059	0.0019	(0.0021, 0.0097)
Poa annua	43708	0.0332	0.0020	(0.0293, 0.0371)

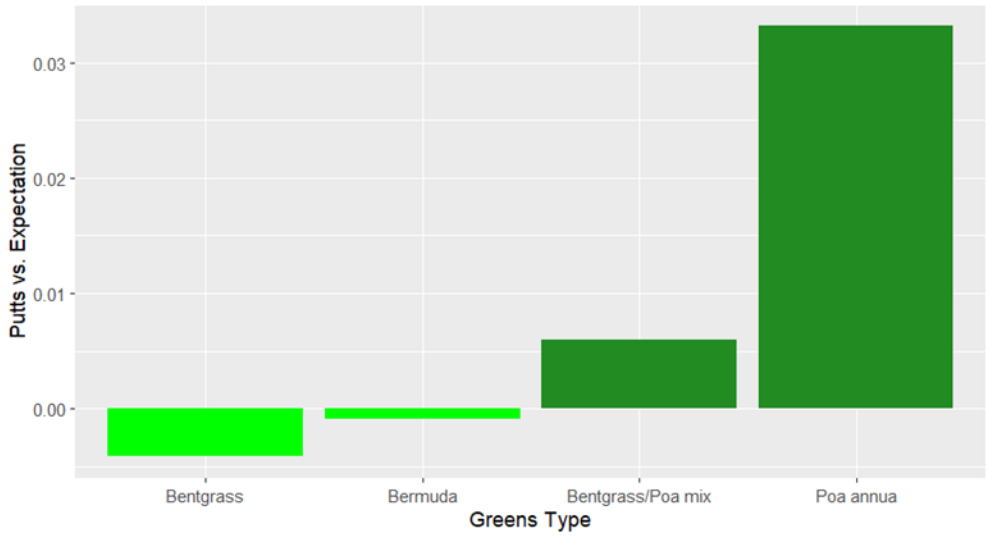

Figure 7. Mean putts difference by grass type (higher = worse performance).

Table 8. Results of ANOVA test comparing putts difference across categories of grass type.

Analysis of Variance Table

Response: Putts.Diff

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Greens_Grouped	3	43	14.3548	128.72	< 2.2e-16	***
Residuals	547518	61059	0.1115			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

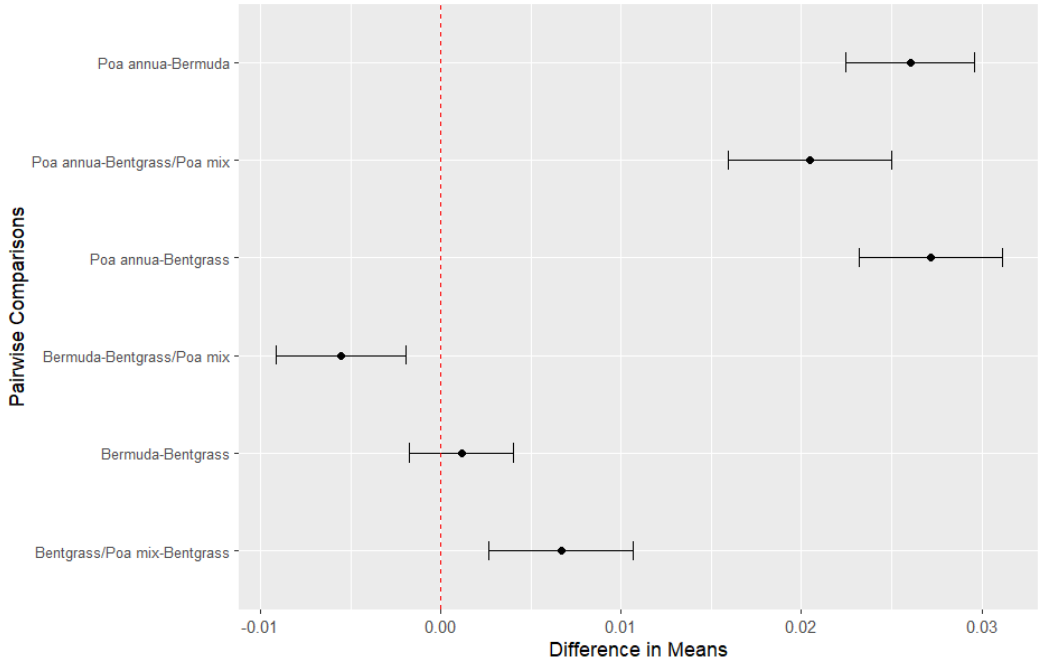

Figure 8. Pairwise Tukey test comparing means between categories of grass type.

RQ2. Does the category of the previous shot (putt, chip, or full shot) affect the chance of a putt being holed? If so, does this effect vary across different surfaces?

Putts that followed another putt had the lowest mean *putts difference* of -0.0166 (Table 9). The one-way ANOVA test (Table 10) showed a significant difference in *putts difference* between categories of previous shot, and the Tukey test (Figure 9) suggested significant differences between all pairs of means.

Table 9. Mean putts difference by category of previous shot with 95% confidence intervals.

Previous Shot Type	n	Mean Putts Difference	Standard Error	95% CI
Putt	50148	-0.0166	0.0016	(-0.0197, -0.0134)
Short Game	68820	0.0022	0.0017	(-0.0012, 0.0055)
Full Shot	64627	0.0091	0.0019	(0.0055, 0.0127)

Short Game – a shot from off the green from 30 yards (90 feet) or less.
Full Shot – a shot from off the green from 80 yards (240 feet) or more.

Table 10. Results of one-way ANOVA test comparing putts difference with category of previous shot.

```
Analysis of Variance Table

Response: Putts.Diff
              Df Sum Sq Mean Sq F value    Pr(>F)
Prev.Shot      2     19  9.6981  51.297 < 2.2e-16 ***
Residuals 183592  34710  0.1891
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

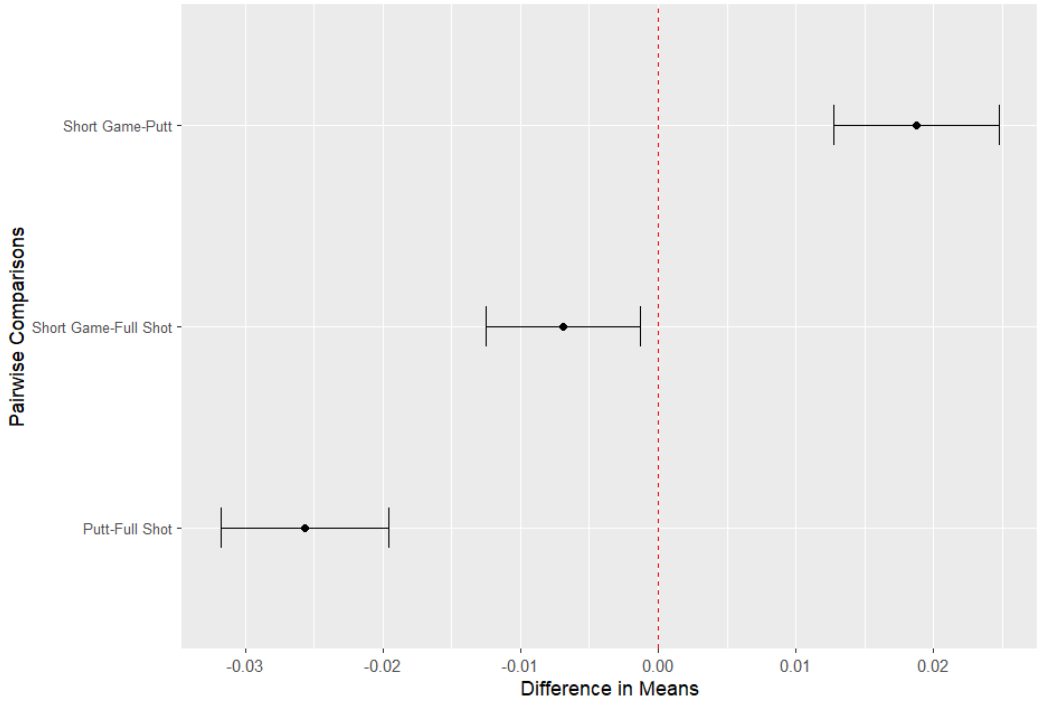

Figure 9. Pairwise Tukey test comparing means between categories of previous shot.

In Table 11, the same statistics are presented for *Poa annua* greens only. The two-way ANOVA (Table 12) did not show a significant interaction between grass type and the category of the previous shot.

Table 11. Mean putts difference by category of previous shot with 95% confidence intervals (*Poa annua* only).

Previous Shot Type	n	Mean Putts Difference	Standard Error	95% CI
Putt	7140	0.0196	0.0048	(0.0103, 0.0289)
Short Game	9508	0.0433	0.0048	(0.0339, 0.0526)
Full Shot	7878	0.0500	0.0054	(0.0395, 0.0606)

Table 12. Results of two-way ANOVA test comparing putts difference with category of previous shot and grass type.

```
Analysis of Variance Table

Response: Putts.Diff
                         Df Sum Sq Mean Sq F value Pr(>F)
Greens_Grouped            3     46 15.4947 82.0707 <2e-16 ***
Prev.Shot                 2     21 10.2955 54.5320 <2e-16 ***
Greens_Grouped:Prev.Shot  6      2  0.3318  1.7575 0.1035
Residuals                 183583  34660  0.1888
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

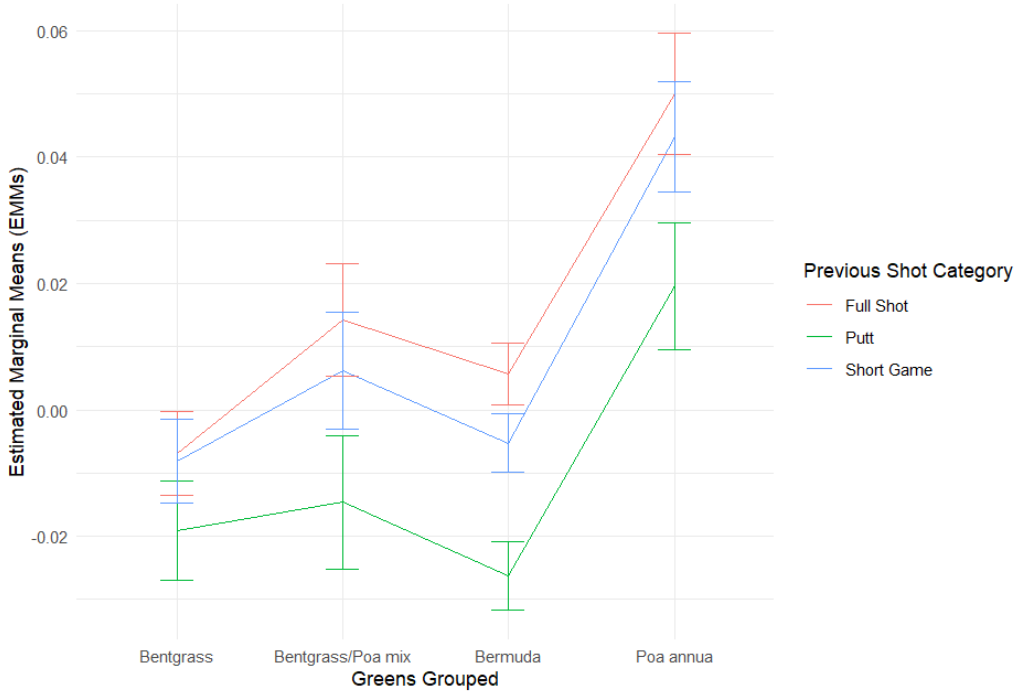

Figure 10. Estimated marginal means comparing grass type and category of previous shot.

RQ3. How do putts on Poa annua greens compare to other surfaces at different starting distances?

Figures 11 and 12 show *putts difference* across distances from 0 to 80 feet, grouped into 10 foot intervals. Figure 11 shows *Poa annua* greens, and Figure 12 shows all greens. The highest *putts difference* on *Poa annua* greens appear to be from 60 to 80 feet.

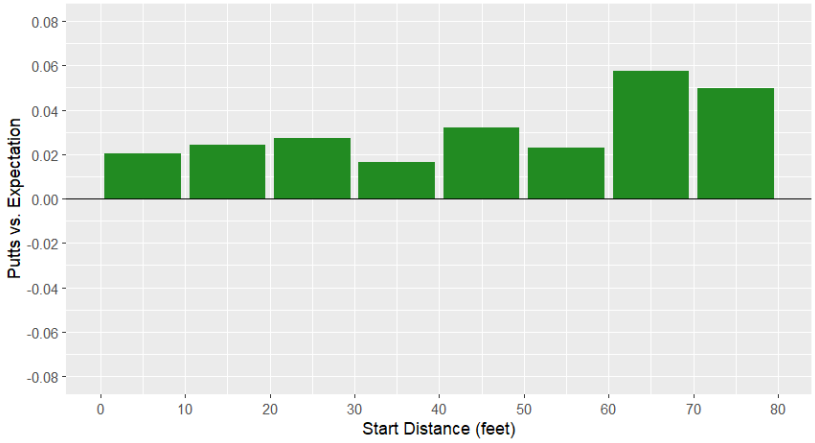

Figure 11. Putts difference by start distance (Poa annua).

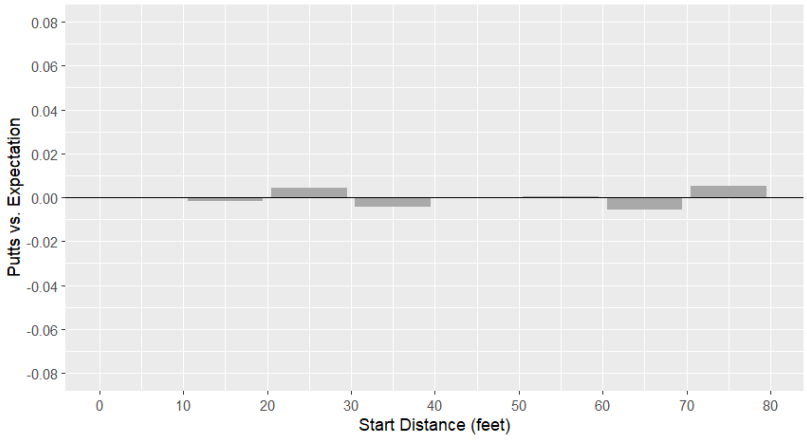

Figure 12. Putts difference by start distance (all greens).

However, when the distances from 0 to 10 feet are shown, the 4 to 7 feet range on *Poa annua* greens appears to have a particularly high *putts difference* (Figure 13). Recall that the *putts difference* measure does not account for a difference between each putt taken between the first putt and the ball being holed, and so a high *putts difference* from long distances does not explain whether this is due to difficulty on the first putt, the second putt, or both.

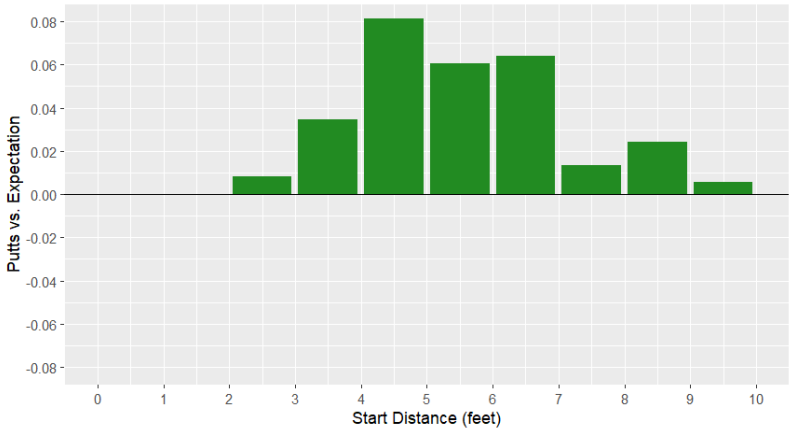

Figure 13. Putts difference by start distance from 0 to 10 feet (*Poa annua*).

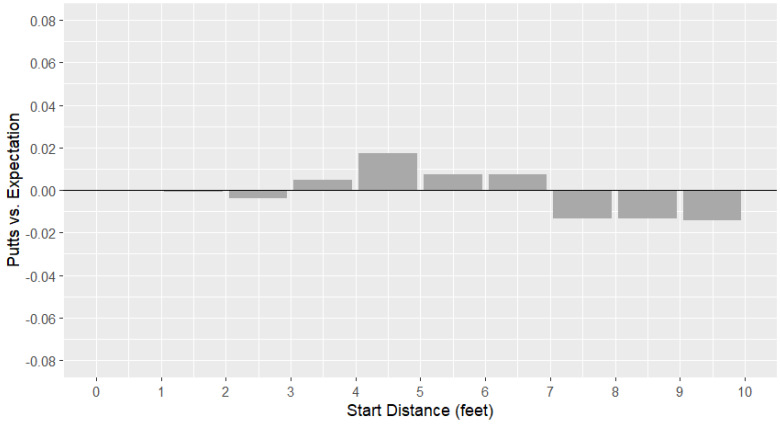

Figure 14. Putts difference by start distance from 0 to 10 feet (all greens).

The *strokes gained* statistic accounts only for the next putt, based on the ending position of the ball and the expected number of putts from that location. Figures 15 and 16 both show *strokes gained* on *Poa annua* greens. Figure 15 is from 0 to 80 feet, and Figure 16 is from 0 to 10 feet. Note that when only the next putt is measured, the 4 to 7 feet range has a much lower strokes gained than all other distances.

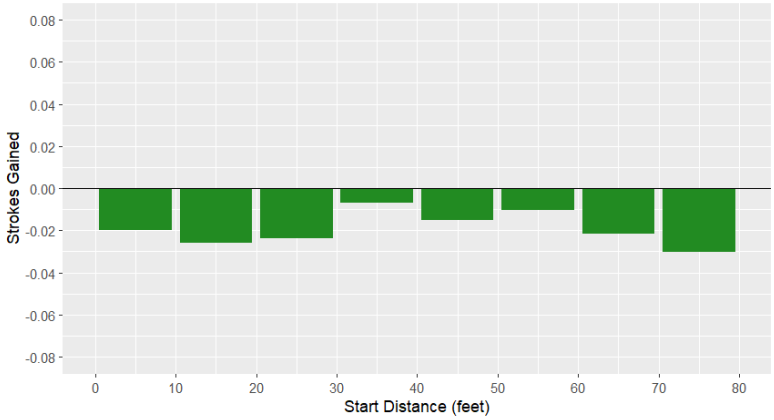

Figure 15. Strokes gained by starting distance (*Poa annua*).

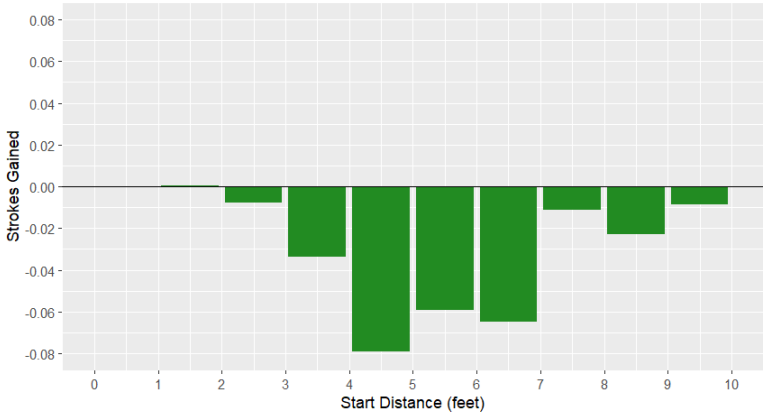

Figure 16. Strokes gained by starting distance, 0 to 10 feet (*Poa annua*).

The linear model in Table 13 shows that there is significant interaction between Poa annua greens and starting distance when predicting *putts difference*. In Table 14, the same test was run predicting *strokes gained*, and significant interaction was also found.

Table 13. Linear model predicting putts difference using starting distance and *Poa annua* green type (binary) plus interaction.

```
Coefficients:
                          Estimate Std. Error t value Pr(>|t|)
(Intercept)             -3.861e-03  1.176e-03  -3.283  0.00103 **
PoaTRUE                  4.297e-02  3.193e-03  13.455  < 2e-16 ***
Start.Distance          -1.909e-05  5.236e-05  -0.365  0.71539
PoaTRUE:Start.Distance  -3.042e-04  1.417e-04  -2.148  0.03174 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.4159 on 346315 degrees of freedom
Multiple R-squared:  0.0009605, Adjusted R-squared:  0.0009519
F-statistic:   111 on 3 and 346315 DF,  p-value: < 2.2e-16
```

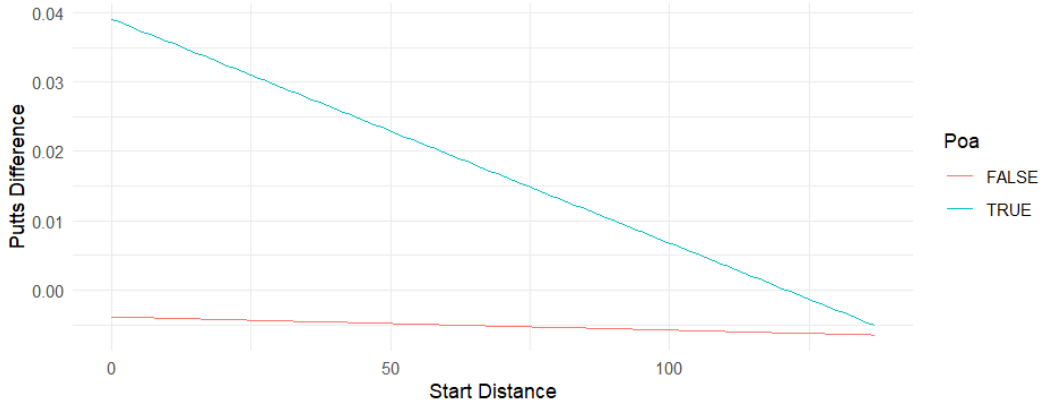

Figure 17. Linear model showing interaction between starting distance and *Poa annua* green type (binary) when predicting putts difference.

Table 14. Linear model predicting putts gained using starting distance and *Poa annua* green type (binary) plus interaction.

```
Coefficients:
                          Estimate Std. Error t value Pr(>|t|)
(Intercept)              3.008e-03  1.114e-03   2.701  0.00692 **
PoaTRUE                 -4.492e-02  3.024e-03 -14.856  < 2e-16 ***
Start.Distance          -2.217e-04  4.958e-05  -4.471 7.80e-06 ***
PoaTRUE:Start.Distance   8.858e-04  1.341e-04   6.604 4.01e-11 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3938 on 346315 degrees of freedom
Multiple R-squared:  0.0007939, Adjusted R-squared:  0.0007853
F-statistic: 91.72 on 3 and 346315 DF,  p-value: < 2.2e-16
```

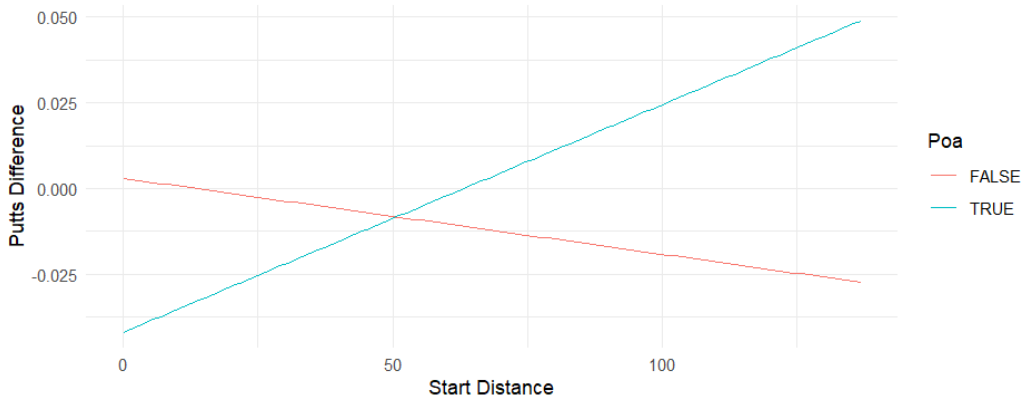

Figure 18. Linear model showing interaction starting distance and *Poa annua* green type (binary) plus interaction when predicting putts gained.

RQ4. Do the best putters tend to perform better or worse on Poa annua, relative to other players?

Table 15 shows the division of players in the dataset by SGP (strokes gained putting). Players in the top quartile had a mean SGP above 0.253 per round.

Table 15. Distribution of quartiles of PGA Tour players by SGP, 2015-16 and 2016-17 seasons.

Minimum	Q1	Median	Mean	Q3	Max
-0.987	-0.180	0.033	0.033	0.253	0.739

Table 16 compares players in each quartile (Quartile 1 contains the best-performing putters) and their mean putts difference on *Poa annua*, relative to their mean putts difference on Bermuda & Bentgrass greens. The difference between the two measures appears to be somewhat consistent across the four quartiles.

Table 16. Mean putts difference by SGP quartile, *Poa annua* vs. Bermuda/Bentgrass.

	Poa annua		Bermuda/Bentgrass		
SGP Quartile	n	Mean Putts Difference	n	Mean Putts Difference	Poa Difference
1	9719	0.0094	52663	-0.0239	0.0333
2	10827	0.0287	60149	-0.0107	0.0394
3	9658	0.0384	55766	0.0038	0.0346
4	9322	0.0496	54607	0.0170	0.0326

The ANOVA test (Table 17) reveals significant differences between the groups of both variables (SGP quartile and green type) but there is insufficient evidence to suggest an interaction between the two variables.

Table 17. Two-way ANOVA test comparing putts difference among categories of SGP quartile and grass type, plus interaction.

```
                            Df Sum Sq Mean Sq F value Pr(>F)
Greens_Grouped               3     40  13.371   84.16 <2e-16 ***
sgp_quartile                 3     66  22.147  139.41 <2e-16 ***
Greens_Grouped:sgp_quartile  9      1   0.129    0.81  0.607
Residuals                295807  46994   0.159
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

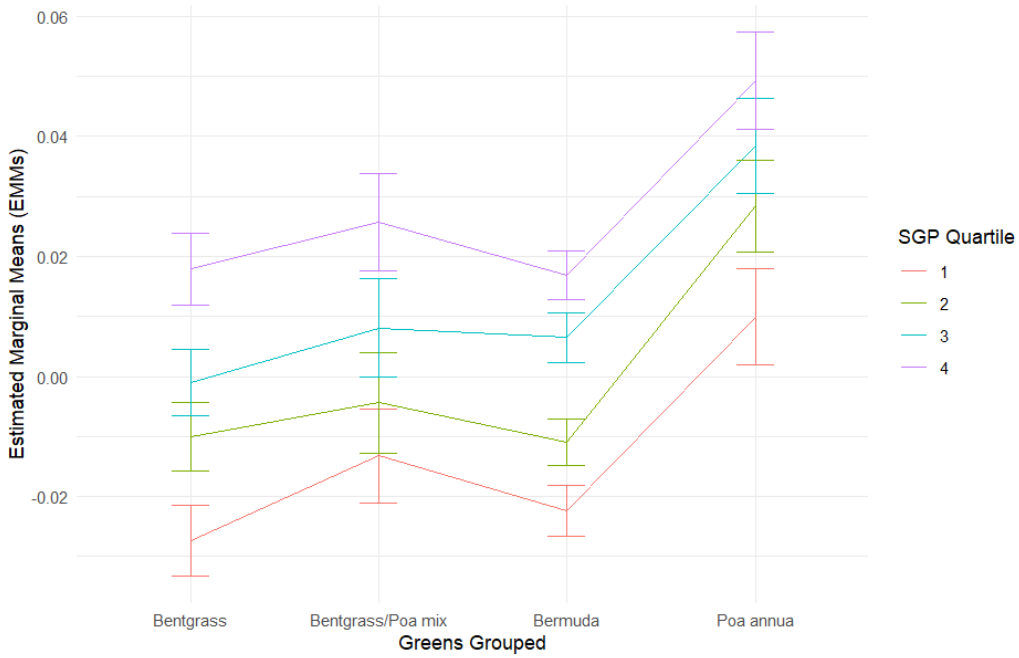

Figure 19. Estimated marginal means comparing grass type and category of SGP quartile.

Discussion

The results of this study reaffirm *Poa annua*’s reputation as a difficult putting surface. In particular, the 4 to 7 foot range appears to be significantly more difficult on *Poa annua* than on other surfaces. If *Poa annua* affects the roll of the ball due to its uneven growth then that could either change the ball’s lateral path, or it could hamper the ball’s speed if it is caused to ‘hop’ in the air rather than remaining in contact with the green as it rolls. It stands to reason that small deviations in the ball’s direction could be the difference between the ball going into the hole or not, which would be worth at least one stroke. However, small deviations in speed may only result in a slightly longer (or sometimes slightly shorter) next putt. Since putts in the 4 to 7 feet range are putts that a professional is expecting to make, it would be intuitive to think that random deviations might affect putts from this range more than any other.

However, one might also assume that adding randomness to a putt would be a ‘leveling’ effect that removes some of the edge held by more highly skilled putters. The evidence in this study did not

support that hypothesis. It is possible that there is also a counteractive factor whereby if a ball is to randomly deviate, then it is beneficial for its path to begin as close to the center of the hole as possible, so that it still might enter the edge of the hole after deviating. In this case, more highly skilled putters would benefit. A possible area of future study would be to use a reliable device that rolls a ball along a desired starting line, and see how putting success varies on different surfaces from various distances. Alternatively, the same study could be run using a computer simulation with variables for players' ability to start the ball on the desired line and the amount of random deviation in the green.

The study also found that professional golfers are slightly more successful on putts that follow a previous putt than putts that follow a shot from off the green. There are two potential reasons for this. Firstly, when the ball rolls past the hole, the golfer gains information about the slope of the green in the area around the hole which may assist him in reading the following putt. Secondly, since balls tend to roll downhill, a putt may be more likely to roll into a position where the subsequent putt is straight uphill, whereas a shot from 150 yards with a lot of spin often stops quickly, uninfluenced by the slope. However, there was insufficient evidence that this effect was associated with grass type.

Future development of this study may involve adjusting the *expected putts* measure for each putt using factors such as weather, player skill, or the difficulty of individual greens. Although this study suggests a higher level of difficulty on *Poa annua* greens, it is still not possible to conclusively state that the *Poa annua* itself is causing the difficulty. It may be the case that the particular PGA Tour courses that use *Poa annua* also have more slope in their greens, more windy venues, or other factors. The PGA Tour's full ShotLink dataset includes data such as the time of day and has three-dimensional (x, y, z) hole and ball locations that would allow for consideration of uphill, downhill, and sidehill lies. However, at time of writing the PGA Tour has made that data proprietary and it is not available for academic study.

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