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Documenting Trends in Nutrient Use and Conservation Practices on US Golf Courses

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Abstract

Between an initial survey in 2007 and a follow-up in 2014, US golf courses have decreased their nutrient use, with annual reductions of 34% (30,970 tons) for N, 53% (17,867 tons) for P_2O_5, and 42% (37, 419 tons) for K_2O (potash). Reductions in the number of fertilized acres, golf course closures, and reductions in nutrient use rates were responsible for the observed trends. There is dramatic, climate-driven regional variation in nutrient use across the United States, with the lowest rates in the cool climates of the Northeast and North Central regions and the highest rates in the warm climates of the Southeast and Southwest regions. Future reductions in nutrient use on golf courses will be facilitated by continued adoption of conservation measures, adoption of lower nutrient use guidelines, additional governmental regulation, and cutbacks in the number of golf courses.

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Abbreviations: GCSAA, Golf Course Superintendents Association of America; KS, Kolmogorov-Smirnov; MLSN, minimum levels for sustainable nutrition; NGF, National Golf Foundation; USGA, US Golf Association.

Conversions: For unit conversions relevant to this article, see Table A.

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Nutrient-use practices on US golf courses were documented for the first time in a 2007 survey conducted by the Golf Course Superintendents Association of America (GCSAA, Lawrence, KS) (Throssell et al., 2009a). Part of a larger effort known as the GCSAA Golf Course Environmental Profile, the nutrient-use survey was one of five national surveys, conducted between 2006 and 2009, with the objective of developing a comprehensive environmental profile of golf courses in the United States (Lyman et al., 2007; Throssell et.al., 2009b; Throssell et al., 2009b; Lyman et al., 2012a; Lyman et al., 2012b). In the fall of 2014, the second phase of the Golf Course Environmental Profile was conducted by the GCSAA through the Environmental Institute for Golf (EIFG, Lawrence, KS) and funded by the US Golf Association (USGA, Far Hills, NJ). The nutrient-use survey was the second of five follow-up surveys. In this report, we summarize the results of the 2014 nutrient-use survey, compare them with results from 2006, and identify where changes have occurred.

Survey Implementation

Of the 15,372 golf facilities in the United States at the time the survey was completed in 2015 (National Golf Foundation [NGF], personal communication, 2015), 13,723 US golf

Table A. Useful conversions.

To convert Column 1 to Column 2, multiply by	Column 1 Suggested Unit	Column 2 SI Unit
0.405	acre	hectare, ha
0.454	pound, lb	kilogram, kg
0.907	ton (2000 lb), ton	megagram, Mg (tonne)

courses managed by superintendents with available email addresses were identified by integrating the GCSAA and NGF databases. An initial email invitation, which included a link to the online survey, was sent to prospective participants in March 2015, followed by three email reminders, which were sent in April 2015. A total of 1529 completed surveys were received (10% of all facilities). This is less than the 16% response coverage from the 2007 survey (Throssell et al., 2009a) (Table S1 in supplemental material), which also included a mail survey campaign. While both surveys targeted the same population, respondents in 2015 were not to the same as those in 2007. Participation in the survey was encouraged by entering respondents into a drawing for a total of twenty-one $100 gift cards and providing a 0.25 service point to GCSAA members in support of their professional development requirements for certification.

Review of Survey Data

Although the survey was implemented in 2015, the data reported by respondents covered management practices for 2014 and earlier. The data reported here on the initial nutrient-use survey (conducted in 2007) covers 2006 and earlier. To gain insights into the survey data, respondents were stratified by agronomic region, as described by Throssell et al. (2009a) (Figure S1, Table S1), and by golf course type, number of holes, and (for public courses) greens fees.

Nutrient Use and Acreage Projections

Analysis of the completed surveys indicated that each agronomic region provided responses in roughly the same proportions as all US golf courses, but those golf courses that were either 9 holes or 18 holes with lower greens fees had responses at lower rates than for the national makeup of golf facilities. To eliminate significant sampling bias, and to ensure that the data were representative of the overall golf course industry in the United States, the response-data means were weighted by classifying respondent-level data into one of 35 groups (cells) based on course characteristics and agronomic region, and then determining the proportion of each group within the total survey response (Table S1). Weighting factors were determined as described by Kish (1990).

Projected national and regional nutrient-use amounts and acreages were estimated by multiplying the appropriate weighted mean by the number of golf courses in each of the 35 cells. This approach, which enhances the projection method by using more distinct, homogeneous facility segments, was used for analysis of both the 2014 and the 2006 datasets. A somewhat different method, which relied on the use of fewer cells, rather than the 35 used here, was used to calculate projected nutrient use and acreage reported previously (Throssell et. al., 2009a). Use of the 35-cell method led to estimates for 2006 projection data that were consistently 9 to 10% lower than those reported by Throssell et al. (2009a) but provide more accurate estimates. Because of the nature of projection data, for which there is no measure of variability, statistical differences are not calculated for these values.

Statistical Analysis

A graphical review of the data from the 2006 and 2014 data revealed a poor fit with the normal distribution for nutrient rate data. Further analysis revealed that these distributions exhibited skewness and kurtosis values (Table S2) that were well in excess of the lower values expected for a normal distribution. Data were then analyzed with the Kolmogorov-Smirnov (KS) goodness of fit test (NIST/SEMATECH, 2015) and determined to have a non-normal distribution. Further testing using Easy Fit distribution fitting software (Mathwave Technologies, 2015) identified the two parameter log-logistic model, or Fisk model (Johnson et al., 1995), as an appropriate fit for calculating the nutrient-use survey data, with KS fit values at 0.10 or less (Table S3). On the basis of this evaluation, the data were fitted to the Fisk distribution using R, version 3.1.2 (R Core Team, 2013) and the VGAM package (Yee, 2014). The non-normal skewed distributions encountered in the nutrient-rate data sets indicate that the median, rather than the mean, is the most appropriate measure of central tendency. All other data collected in the survey followed a normal distribution, and for this reason, means were used as the most appropriate measure of central tendency for the remaining data. To determine levels of significance among groups, the Wilcoxon rank sum test (Moore et al., 2007), which is appropriate for both normal and non-normal data, was applied. The Bonferroni correction was used to provide for multiple tests of significance (Hochberg, 1988). Values were considered significantly different when $p \leq 0.10$.

The use of the Fisk median to estimate nutrient rates resulted in different, and generally lower, nutrient rate values than were previously reported in the initial 2006 nutrient-use survey (Throssell et. al., 2009a). Therefore, both the 2006 and 2014 data describing nutrient rates used at individual golf courses was reanalyzed with the same methods (median of the Fisk distribution).

Statistical separation of proportional data was conducted using R and the gmodels package ver. 2.15.4 (Warnes et al., 2015) two-sample test for equality of proportions with continuity correction using a Chi-square comparison, where p was less than or equal to 0.10. To evaluate the role of climate on nutrient-use practices, we matched each respondent's zip code to 30-year normal (1981–2010) data sets for precipitation (PRISM Climate Group, 2014).

Trends in National Nutrient Use: 2006 and 2014

Since 2006, US golf courses have reduced their N, P_2O_5, and K_2O use by 34, 53, and 42%, respectively. These declines represent an annual savings of an estimated 30,970 tons of N, 17,867 tons of P_2O_5, and 37,419 tons of K_2O (Table 1) and were achieved through two approaches: (i) reductions in the number of acres fertilized with N, P_2O_5, and/or K_2O; and (ii) reductions in the rate of each of these nutrients applied per unit area.

Reduction in Fertilized Acres

When asked whether the acreage at their facility had changed over the last 5 years, 27% of respondents reported that they had voluntarily reduced their acreage since 2009. Projecting from this data, an estimated 4166 US golf courses reduced their fertilized acreages between 2009 and 2014 (data not shown), which resulted in a 16% reduction in acres fertilized with N, 46% in acres fertilized with P_2O_5, and 22% in acres fertilized with K_2O (Table 2). The greatest reductions in fertilized acreages occurred in fairways and roughs, especially with P_2O_5 applications. Greens are the most likely feature to be fertilized, and roughs the least likely (Table 3).

Fertilized turf acreages were further reduced in a less voluntary manner due to a net decline of 618 golf facilities between 2006 and 2014. All regions except the Upper West/Mountain had decreases in the number of facilities, and the North Central, Southeast, and Transition regions had the greatest decreases. Although this decline is neither a positive trend for the golf industry nor a prescription for future conservation efforts, the reduced number of golf facilities in the United States did result in fewer golf course acres, and therefore a nutrient savings of 3519 tons of N, 1115 tons of P_2O_5, and 3190 tons of K_2O (Table 4).

Reduced Nutrient Application Rates

Reductions in the rates of nutrients applied per unit area also contributed to decreased nutrient use (Tables 5 and 6). For example, the median N rate used nationwide declined from 2.75 to 2.17 lb/1000 sq ft—a 21% reduction—from 2006 to 2014, while P_2O_5 rates decreased by 63% and K_2O rates by 38% during that same time period (Table 6). Greens were treated with the highest rates of each nutrient, followed, in descending order, by tees, practice areas, fairways, grounds, and roughs. Rate reductions made since 2006 were largest on tees. Fertilizer rates were highest on greens and tees (Tables S4–S6), probably because of the need for recovery from low mowing heights, high concentrations of traffic, and high golfer expectations for playability and quality.

The dramatic decrease in nutrient use rates that occurred between 2006 and 2014 were made without apparent declines in turf quality and playability. Those effects could be due to storage of excess nutrients in the soil, and as a result, we expect that as the soil's nutrient reserves are depleted, fertilizer rates will not continue to decline at the same level, and may even increase.

In the period between 2006 and 2014, there was also a change in the relative ratios of N, P_2O_5, and K_2O used, such that lower percentages of P_2O_5 and K_2O were used in 2014. This reduction presumably is a reflection of the regulatory pressures that have caused both fertilizer manufacturers and golf course superintendents to shift toward lower use rates, particularly of P_2O_5 (Table S7).

Conservation Practices

The nutrient rate reductions described previously were achieved through adoption of conservation measures that explained almost half of the decreases observed from 2006 to 2014 (Table 5). The most commonly cited conservation practices include fertilization based on soil-test results, return of clippings, precision fertilizer application, and reduction of turf acreage (Fig. 1).

Despite the fact that respondents said that they used soil tests to reduce reliance on fertilizers, higher use rates were observed for respondents who conducted soil tests (Table 7). This apparent contradiction may be due to some of the turf fertility guidelines currently in use, which target higher nutrient levels than are required for acceptable turf growth. For example, guidelines based on the SLAN (sufficiency level of available nutrients) approach identify a range of 50–116 ppm K and 26–54 ppm P (Carrow et. al., 2004), whereas newer guidelines, such as those for minimum levels for sustainable nutrition (MLSN) identify 37 ppm K and 21 ppm P (Stowell and Woods, 2013). As a result, those who conduct soil tests with the belief that it will help them to reduce fertilizer inputs may end up unintentionally increasing those inputs instead, probably because the guidelines used to evaluate their results may be higher than necessary.

In 2014, greens were the most frequently tested feature, followed in descending order by fairways, tees, and roughs. Since 2006 there has been a small but statistically significant national trend toward less use of soil tests on most golf course features (Table S8). This reduction may be due to budgetary restrictions that occurred during the recent financial recession.

A decline in the use of winter overseeding has also contributed to conservation. Winter overseeding of warm-season turf with cool-season turf varieties results in the use of significantly more N, P_2O_5, and K_2O and is most common in warmer climates, primarily in the

Table 1. Projected regional and national nutrient use, 2006 and 2014.

Region	N				P_2O_5				K_2O			
	2006	2014	Change		2006	2014	Change		2006	2014	Change	
	tons			%	tons			%	tons			%
North Central	15,047	10,612	–4,435	–30	4,657	1,421	–3,236	–70	11,960	7,142	–4,818	–40
Northeast	9,139	6,560	–2,579	–28	3,483	1,152	–2,331	–67	8,090	4,719	–3,371	–42
Pacific	3,110	2,124	–986	–32	1,123	966	–157	–14	2,697	1,949	–748	–28
Southeast	32,532	18,894	–13,638	–42	11,114	5,144	–5,970	–54	37,246	20,478	–16,768	–45
Southwest	13,247	8,986	–4,261	–32	5,408	3,053	–2,355	–44	12,127	6,397	–5,730	–47
Transition	13,600	9,688	–3,912	–29	5,876	3,064	–2,812	–48	12,670	8,354	–4,316	–34
Upper West/ Mountain	5,510	4,350	–1,160	–21	1,965	960	–1,005	–51	4,334	2,666	–1,668	–39
Total US	92,185	61,214	–30,971	–34	33,626	15,760	–17,866	–53	89,124	51,705	–37,419	–42

Table 2. Voluntary reductions in fertilized acreage and the nutrient savings that resulted.

Region	N				P_2O_5				K_2O			
	2006	2014	Change	Savings	2006	2014	Change	Savings	2006	2014	Change	Savings
	acre		%	tons	acres		%	tons	acres		%	tons
North Central	279,185	230,025	–18	2,248	222,890	87,951	–61	2,057	264,087	199,216	–25	2,261
Northeast	161,846	134,774	–17	1,297	143,916	57,360	–60	1,697	157,981	121,645	–23	1,425
Pacific	42,969	34,707	–19	504	41,553	27,546	–34	488	42,467	31,495	–26	669
Southeast	280,685	234,015	–17	3,761	237,648	138,002	–42	3,689	268,337	219,974	–18	4,529
Southwest	118,683	93,383	–21	2,425	99,658	75,983	–24	928	113,167	81,642	–28	2,472
Transition	210,663	178,741	–15	1,738	189,959	101,034	–47	2,712	204,407	155,772	–24	2,648
Upper West/ Mountain	85,023	80,419	–5	251	68,766	52,704	–23	280	76,520	64,791	–15	485
Total US	1,179,054	986,064	–16	12,224	1,004,391	540,581	–46	11,851	1,126,966	874,535	–22	14,489

Table 3. Percentage of 18-hole facilities that apply fertilizer to each feature.†

Feature	N		P_2O_5		K_2O	
	2006	2014	2006	2014	2006	2014
Greens	98 a	98 a	93 b	80 a	96 b	95 a
Tees	97 a	96 a	90 b	66 a	95 b	90 a
Fairways	97 b	95 a	85 b	54 a	94 b	86 a
Roughs	80 b	74 a	68 b	37 a	76 b	64 a

† For each 2006-2014 comparison, values followed by the same letter are not significantly different at the 90% confidence level.

Table 4. Projected changes in nutrient use due to reductions in the number of golf facilities, 2006–2014.

	Number of US golf facilities				Projected change 2006–2014		
	2006	2014	Change, 2006–2014	Change	N	P_2O_5	K_2O
				%	tons		
North Central	4,123	3,920	–203	–5	–708	–184	–496
Northeast	2,739	2,690	–49	–2	–156	–49	–119
Pacific	629	615	–14	–2	–70	–24	–51
Southeast	3,216	3,020	–196	–6	–1815	–555	–1,868
Southwest	1,221	1,208	–13	–1	–136	–51	–109
Transition	2,951	2,793	–158	–5	–705	–274	–594
Upper West/ Mountain	1,111	1,125	14	1	70	21	47
Total US	15,990	15,371	–619	–4	–3519	–1115	–3190

Table 5. Summary of factors contributing to reduced projected nutrient use, 2006–2014.

Nutrient	Total nutrient reduction, 2006–2014	Reduced turf acreage				Reduced nutrient use rates	
		Fewer facilities		Voluntary acreage reductions		Conservation practices	
	tons	tons	% of total reduction	tons	% of total reduction	tons	% of total reduction
N	–30,969	3519	11.4	12,224	40	15,226	49
P_2O_5	–17,867	1115	6.2	11,851	66	4901	27
K_2O	–37,419	3190	8.5	14,489	39	19,740	53

Table 6. Nutrient use rates in 2006 and 2014 for 18-hole golf courses and the climatic factors that affect them.†

Region	N		P_2O_5		K_2O		Active turf growth (months/year)
	2006	2014	2006	2014	2006	2014	
	lb 1000 sq ft^{-1} yr^{-1}						
North Central	2.22 a	1.70 a*	0.53 a	0.16 a*	1.78 a	1.0 ab*	5–7
Northeast	2.33 ab	1.93 ab*	0.72 b	0.18 a*	1.93 a	1.3 bc*	6–7
Pacific	2.55 bc	2.23 b	0.80 bc	0.46 bcd*	2.08 ab	1.3 bcd*	7–11
Southeast	4.22 d	2.95 c*	1.18 d	0.50 cd*	4.36 d	2.6 e*	12
Southwest	4.22 d	3.14 c*	1.43 d	0.88 d*	3.44 c	2.2 de*	12
Transition	2.51 bc	2.13 b*	0.93 c	0.28 abc*	2.32 b	1.5 cd*	9
Upper West/ Mountain	2.73 c	2.03 ab*	0.76 bc	0.25 ab*	2.07 ab	0.9 a*	5–9
Total US	2.75	2.17*	0.82	0.30*	2.38	1.47*	

* Significant at the 90% confidence level.

† Within each column, values followed by the same letter are not significantly different at the 90% confidence level. All values shown are medians. Active turf growth periods were determined by identifying the number of months when growth potential (Gelernter and Stowell, 2005) for either cool-season or warm-season turf was 20% or more.

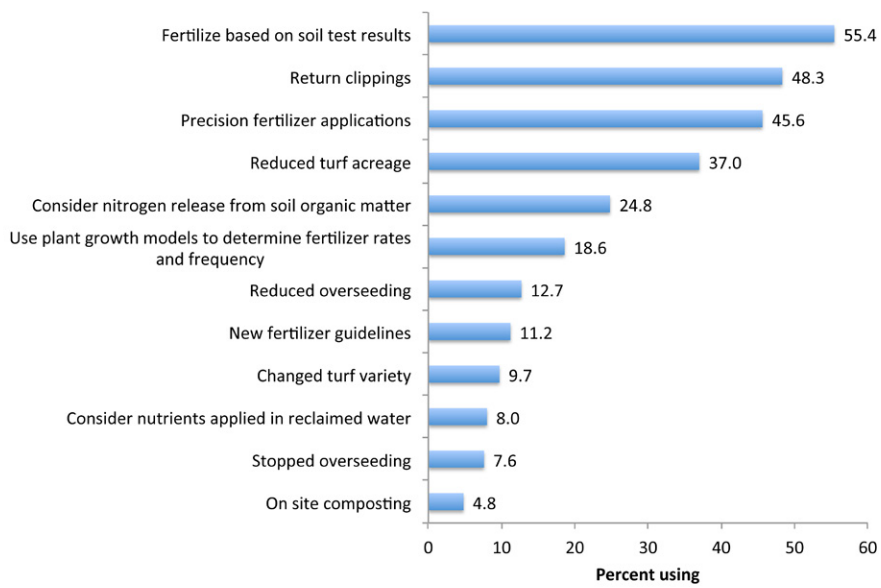

Fig. 1. Practices used by 2014 survey respondents to reduce reliance on fertilizers.

Southeast, Southwest, and Transition regions (Tables 8 and 9). In 2014, 8% of respondents from across the United States reported that they had stopped overseeding, and 13% reported reducing overseeding (Fig. 1). For a more realistic assessment of changes in overseeding patterns, however, we restricted the data to only those three regions where overseeding is most common. Within this data subset, the percentage of respondents who elected to either stop or reduce overseeding was predictably much higher (Table 9). The features most likely to be overseeded were tees, and the least likely were roughs (Table 9).

Table 7. Influence of soil testing on nutrient use for a typical 18-hole golf course, 2014.†

Feature	N		P_2O_5		K_2O	
	Soil test	No soil test	Soil test	No soil test	Soil test	No soil test
	lb/1000 sq ft					
Greens	3.71 b	3.22 a	1.07 b	0.73 a	4.04 b	2.44a
Tees	3.35 b	2.79 a	0.96 b	0.77 a	2.80 b	1.87 a
Fairways	2.78 b	2.17 a	0.83 a	0.74 a	2.15 b	1.44 a
Roughs	2.16 b	1.87 a	0.74 a	0.72 a	1.71 b	1.35 a

† For each nutrient, values in the same row followed by the same letter are not significantly different at the 90% confidence level.

Table 8. Increased nutrient use due to overseeding in the Southwest, Southeast, and Transition regions for 2014.†

Feature	N		P_2O_5		K_2O	
	Overseeded	Not overseeded	Overseeded	Not overseeded	Overseeded	Not overseeded
	lb/1000 sq ft					
Greens	3.38 b	2.34 a	1.03 b	0.39 a	2.93 b	1.90 a
Tees	2.55 a	2.38 a	0.52 a	0.41 a	2.13 a	1.94 a
Fairways	2.91 b	2.36 a	0.68 b	0.41 a	2.46 b	1.93 a
Roughs	3.03 b	2.41 a	0.98 b	0.42 a	2.01 a	2.02 a

† All values shown are medians. Values within each nutrient followed by the same letter are not significantly different at the 90% confidence level.

Table 9. Overseeding practices of survey respondents in 2014 in the three regions where overseeding is most common.

	Conservation-driven changes in overseeding practices		Overseeding by feature				No overseeding at all
	Overseeding stopped	Overseeding reduced	Greens	Tees	Fairways	Roughs	
	%						
Southeast	20	24	28	59	20	3	37
Southwest	10	33	41	69	43	30	30
Transition	11	20	6	33	8	6	62

Factors Considered in Nutrient-Use Decisions

The factors involved in nutrient use decision-making changed minimally from 2006 to 2014. However, of the factors that became more important during this period—regulatory restrictions, economics, and adoption of university recommendations (Table 10)—bear further discussion.

Regulatory Restrictions

Respondents reported that the number of restrictions on fertilizer application has risen since 2006 (Table 11). Restrictions on the use of P were the most commonly cited, and they became more extensive, from 5% of 18-hole golf courses having restrictions in 2006 to 19% in 2014 (Table 11), probably because of increasing concerns about and legislation to the role of P in eutrophication and the lower quality of water sources (Rice and Horgan, 2010). These restrictions on use of P, and to a lesser extent, N, had a significant impact that can be observed in trends in overall nutrient use (Table 1) and in nutrient use rates (Table 12). Phosphate restrictions were most frequently reported from the Pacific region (94%), followed by the North Central (93%), Northeast (89%), Transition (74%), Southeast (52%), Upper West/Mountain (36%), and Southwest (0%) regions (data not shown). This data aligns well with the distribution of states that have enacted P restrictions (Miller, 2012). Regulations targeted at lower fertilizer runoff (date restrictions, buffer strips, no-apply zones), though less frequently cited, have also increased since 2006 (Table 11).

The frequency with which nutrient management plans and programs have been developed has not risen since 2006. In 2014, such plans and programs were much more likely to be developed than were written regional guidelines for best management practices (Table S9).

Economics

As described previously, the net decrease of 618 golf facilities between 2006 and 2014, which was largely

Table 10. Factors involved in nutrient use decisions.†

	2006	2014
Precipitation/temperature/weather	4.16 a	4.17 a
Visual observation/scouting	4.12 a	4.14 a
Previous product performance	4.12 a	4.12 a
Soils/soil analysis	4.23 b	4.10 a
Disease problems/pressure	4.06 b	3.97 a
Turf species	4.08 b	4.00 a
Traffic/wear	3.86 a	3.95 b
Cost of fertilizer	3.60 a	3.82 b
Golfer expectations	3.88 a	4.00 b
Length of growing season	3.80 a	3.80 a
Reduced environmental impact	NA‡	3.71
Golf events calendar	3.62 a	3.67 a
Clipping production	3.50 a	3.60 b
Regulatory requirements	2.80 a	3.16 b
University recommendations	2.83 a	2.94 b
Turf growth prediction models	2.92 a	3.01 b
Manufacturer recommendations	2.80 a	2.87 b
Consultant/service provide recommendations	2.72 b	2.62 a
Tissue analysis	2.75 b	2.65 a
Nutrient content of reuse (effluent, reclaimed, recycled) water source	2.29 a	2.23 a
Adjacent property owners' maintenance standards	2.05 a	2.22 b

† Respondents rated factors on a 1–5 scale, where 1 = not important at all, and 5 = extremely important. Values shown represent the mean score for all respondents. Values within each two-column row that are followed by the same letter are not significantly different at the 90% confidence level

‡ Not asked in 2006.

Table 11. Types of federal, state, local government, or tribal authority restrictions on fertilizer applications reported by 18-hole facilities.†

	2006	2014
	% 18-hole facilities with restrictions	
Nutrient restrictions of any type	8 a	24 b
Phosphorus (total yearly amount or amount/application)	5 a	19 b
Required buffer strips	3 a	8 b
Date restrictions for applications	<1 a	8 b
No-apply zones	2 a	7 b
N (total yearly amount or amount/application)	2 a	6 b
Regional/state stormwater management plan	2 a	5 b
K (total yearly amount or amount/application)	<1 a	<1 a

† Values followed by the same letter are not significantly different at the 90% confidence level.

Table 12. Influence of federal, state, tribal, and local restrictions on nutrient use rates on 18-hole golf courses in 2006 and 2014.†

	2006		2014	
	N	P_2O_5	N	P_2O_5
	lb/1000 sq ft			
Restrictions	2.42 a	0.54 a	2.12 a	0.20 a
No restrictions	2.74 a	0.98 b	2.16 a	0.40 b

† Values within each column followed by the same letter are not significantly different at the 90% confidence level.

exacerbated by the Great Recession, has driven roughly 10% of the nutrient use reductions reported here (Table 5). In addition, fertilizer costs have become more important in nutrient use decisions (Table 10). According to the USDA's Economic Research Service, the average cost of P- or K-based fertilizers has increased by more than 100% between 2006 and 2013 (the last year that data were collected), and the cost of N-based fertilizers has risen by more than 60% (USDA Economic Research Service, 2013).

Golf course size also has had an impact, with 9- and 18-hole golf courses using significantly less N and K_2O per unit area than golf courses with 27 or more holes. Public golf courses used significantly less N and K_2O per unit area than private golf courses (Table S10).

Nutrient Guidelines

Respondents reported greater importance of university recommendations in making nutrient application decisions since 2006 (Table 10). Reliance on these current, science-based recommendations, when combined with interpretation of soil-test data using more accurate nutrient guidelines, such as MLSN (Stowell and Woods, 2013), should contribute to further nutrient use reductions in the future.

Trends in Regional Nutrient Use

Variation among Regions

There was variation in nutrient rates among the nation's seven agronomic regions that was driven primarily by climate. For example, the lowest nutrient rates for 2014 were observed in the North Central and Northeast regions, which have the shortest periods of active turf growth. Conversely, the highest nutrient rates occurred in the Southeast and Southwest regions, which have the longest active growth periods (Table 6). Frequent use of overseeding in the Southwest and Southeast regions (Table 9), which requires significantly more of each major nutrient than non-overseeded turf (Table 8), also contributed to higher nutrient rates in those two regions.

There also was variation among regions in the projected number of tons of N, P_2O_5, and K_2O used for all golf courses (Table 1), although the patterns of variation differ somewhat from those for nutrient rates. This variability resulted not only from the large role of climate within regions, but also the number of golf courses in each region (Table 4). For example, the Pacific region, which has an intermediate period of active turf growth (Table 6), still has the lowest regional nutrient use because it has the fewest golf courses of any region. Similarly, the North Central region, which has the shortest period of active growth, uses the second highest amount of N in the country because it has more golf courses than any other region.

The mean acreage fertilized with N, P_2O_5, or K_2O also varied considerably among regions, with the lowest fertilized acreages occurring in the North Central and Northeast regions and the highest occurring in the Southeast and Southwest regions. This observation is primarily a function of regional differences in golf course size, with the largest golf courses (Southwest, Upper West/Mountain, and Southeast regions) fertilizing the greatest number of acres. The greatest reductions in fertilized acreage from 2006 to 2014 occurred in the Southwest (for N), the North Central (for P_2O_5), and the Upper West/Mountain, North Central, and Transition regions (for K_2O) (Table S11).

Variation within Regions

In addition to the observed variation in nutrient use among regions (Table 6), there was also significant variation in nutrient use within each agronomic region. As seen in Fig. 2, some regions (North Central, Northeast) exhibit a relatively small range of nutrient rates, which indicates that climatic conditions are relatively homogenous within that area on an annual basis. For these regions, median nutrient rate values provide fairly accurate descriptions of the majority of facilities. In contrast, the diverse climatic conditions that characterize the Pacific region (which spans the hot and dry Central Valley of California and the much cooler climate of Alaska) or the Southwestern region (which spans the deserts of Arizona, Nevada, and California and the tropical environment of Hawaii) produce much larger ranges of nutrient rates. For example, while the median N rate for the Pacific region in 2014 was 2.23 lb/1000 sq ft, rates reported from individual facilities ranged from almost zero to over 6.0 lb/1000 sq ft per year (Fig. 2). Similarly, the Southwest region's annual K_2O use ranged from near zero to over 8 lb/1000 sq ft per year, although the median rate was 2.2 lb/1000 sq ft.

Trends in the Use of Nitrogen Sources

Organic fertilizers (materials derived from either plant or animal products containing one or more elements, other than C, H, or O, which are essential for plant growth) were used on 64% of all 18-hole facilities in 2014, consistent with use in 2006 (Table S12). Relatively high percentages of P_2O_5 in some organic fertilizer sources may limit their further adoption, due to increasing restrictions on the use of P_2O_5 (Table 11).

Organic products based on animal waste were used by 65% of those who apply organic fertilizers, making this the most common source, followed by local sewage sludge (39%), crop products such as soybean or corn meal (14%), and food waste, including composted products (13%) (data not shown).

Nitrogen fertilizers are available in quick-release (water-soluble) formulations, as well as slow-release and water-insoluble formulations. In 2014, most N used was in a slow-release formulation, with little change in use patterns since 2006 (Table S13). However, it is notable that in both 2006 and 2014, the Southwest region reported the highest percentage use of quick-release N. It is likely that this region's low annual rainfall is responsible for this

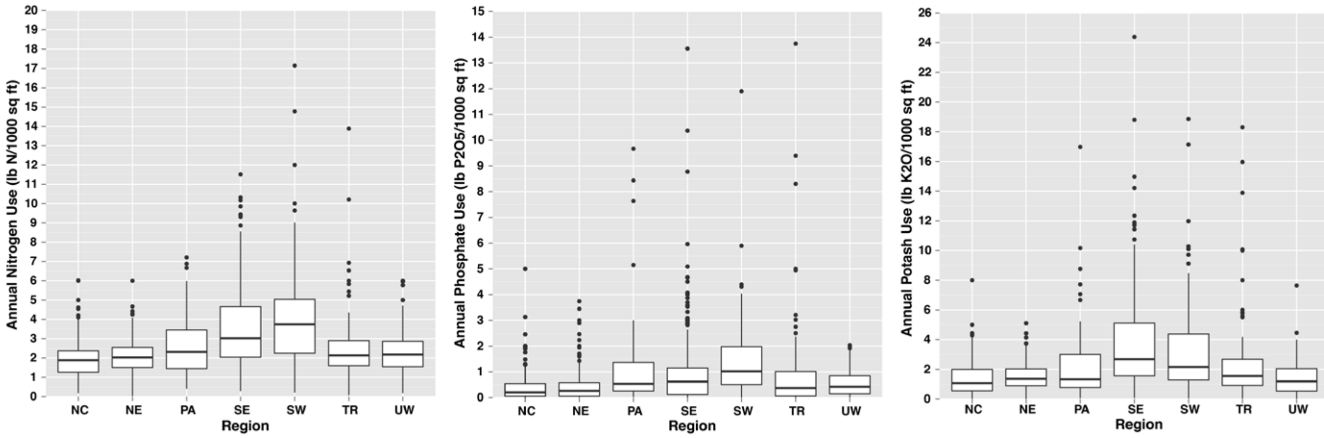

Fig. 2. Regional variation in N, P_2O_5, and K_2O rates for 18-hole golf courses in 2014. The horizontal line in each box represents the median. Each box is bound by the first and third quartiles (25th and 75th percentile values). The upper and lower "whiskers" associated with each box extend to the highest or lowest values, respectively, that are within 1.5 times the inter-quartile range (distance between the first and third quartiles). Data beyond the whiskers are outliers and plotted as points. Extreme outliers were excluded if they exceeded the 95th percentile ($p > 0.95$) of the best-fit Fisk distribution. NC, North Central; NE, Northeast; PA, Pacific; SE, Southeast; SW, Southwest; TR, Transition; UW, Upper West/Mountain.

trend, since quick release N is less likely to move to surface or groundwater in low-rainfall areas.

The popularity of slow-release products is based on convenience and reduced labor input (since fewer applications are required), less risk of foliage burn, and lower probability of leaching into groundwater when used properly. Their cost is higher, however, which may explain the overall flat adoption rate during the years of the Great Recession.

Trends in the Use of Amendments and Supplements

A wide variety of amendments and supplements are applied to improve physical and chemical properties of the soil. In 2014, the most commonly applied products included humic materials, amino acids and proteins, gypsum, and biostimulants. Although the use of almost all amendments and supplements has risen significantly since 2006, the greatest increase in adoption occurred for S, compost teas, $CaCl_2$, microbial inoculants, and gypsum (Table S14).

Calibration, Application, and Storage

Calibration of fertilizing equipment helps ensure that the fertilizer is not being applied at rates that are either too high or too low. The frequency with which equipment is calibrated before application of fertilizers has changed little since 2006. Applications on fairways and roughs were more frequently calibrated than those for greens and tees (Table S15). This may be the result of much larger fertilized acreage associated with those features and therefore greater economic and environmental incentives for accuracy.

In 2014, the number of annual fertilizer applications increased for all features except roughs (Table S16). This trend, when combined with data illustrating large reductions in nutrient rates (Table 6) indicates that superintendents are applying smaller amounts of fertilizer at higher frequencies than in the past. This practice has multiple benefits, including minimizing potential nutrient runoff, more precise calibration of fertilizer rates with turf growth rates, quality goals, and management of clippings. As might be expected, regions with the longest growing season and highest rainfall, such as the Southeast, had the highest number of fertilizer applications per year, especially on greens, whereas cooler regions with fewer active turfgrass growing months had the lowest number of applications (Table S16, Table 6). Greens received by far more fertilizer applications than any other golf course feature. This is to be expected, in part because greens are treated with higher rates of fertilizer (Tables S4–S6), but also because dispensing fertilizer in smaller doses is a means of preventing growth surges.

Improved fertilizer storage facilities help limit the risk of accidental environmental contamination. Since 2006, there has been a large increase—from 46 to 65%—in the number of golf courses storing fertilizer in a facility designed for fertilizer storage that, at a minimum, has an impervious floor, a cover, ventilation, security (locked and with restricted access), and containment features to prevent loss to the environment and/or contamination from runoff (Table S17). This positive trend has occurred despite the cost of the modifications needed for these improved facilities.

CONCLUSIONS AND RECOMMENDATIONS

- Significant reductions in nutrient use have occurred during the past 8 years due to a combination of voluntary conservation practices, regulatory restrictions, golf facility closures, and economically driven decisions.

- Management practices such as reductions in overall and/or fertilized turf acreage, decreased winter overseeding, and precision fertilizer applications will be necessary for further nutrient conservation and will have the added benefit of supporting water conservation efforts.
- The use of nutrient management plans and fertilizer programs has not increased since 2006. Though significant reductions in nutrient use have been achieved despite this plateau in adoption, these plans and programs can assist superintendents in planning, budgeting, and implementing further conservation efforts and should be emphasized in the future.
- Golf courses have and will likely continue to deal with increased regulatory restrictions on fertilizer use, particularly of P, and should be prepared to deal with this ongoing trend.
- Soil test results should be interpreted using the most current, region-appropriate soil-nutrient and plant-requirement guidelines to minimize environmental impact and unnecessarily high fertilizer application rates. Stronger and more coordinated education and extension efforts will be critical toward achieving this goal.

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References

Carrow, R.N., L. Stowell, W. Gelernter, S. Davis, R.R. Duncan, and J. Skorulski, 2004. Clarifying soil testing: III. SLAN sufficiency ranges and recommendations. Golf Course Manage. January: 194–198.

Gelernter, W., and L. Stowell, 2005. Improved overseeding programs 1. The role of weather. Golf Course Manage. March: 108–113.

Hochberg, Y. 1988. A sharper Bonferroni procedure for multiple tests of significance. Biometrika 75:800–802. doi:10.1093/biomet/75.4.800

Johnson, N.L., S. Kotz, and N. Balakrishnan. 1995. Continuous univariate distributions. 2nd ed. Wiley & Sons, Hoboken, NJ.

Kish, L. 1990. Weighting: Why, when and how. In: JSM Proceedings. Section on Survey Research Methods. American Statistical Association, Alexandria, VA. p. 121–130.

Lyman, G.T., M.E. Johnson, G.A. Stacey, and C.D. Brown. 2012a. Golf course environmental profile measures energy use and energy management practices. Appl. Turfgrass Sci. doi:10.1094/ATS-2012-0228-01-RS

Lyman, G.T., M.E. Johnson, G.A. Stacey, and C.D. Brown. 2012b. Golf course environmental profile measures pesticide use practices and trends. Appl. Turfgrass Sci. doi:10.1094/ATS-2012-1220-01-RS

Lyman, G.T., C.S. Throssell, M.E. Johnson, G.A. Stacey, and C.D. Brown. 2007. Golf course profile describes turfgrass, landscape and environmental stewardship features. Appl. Turfgrass Sci. doi:10.1094/ATS-2007-1107-01-RS

Mathwave Technologies. 2015. EasyFit data analysis and simulation. www.mathwave.com/easyfit-distribution-fitting.html (accessed 9 Nov. 2015).

Miller, K.L. 2012. State laws banning phosphorus fertilizer use. OLR Research Report 2012-R-0076. Office of Legislative Research of the Connecticut General Assembly. https://www.cga.ct.gov/2012/rpt/2012-R-0076.htm (accessed 31 Oct. 2015).

Moore, D.S., G.P. McCabe, and B. Craig. 2007. Introduction to the practice of statistics. 6th ed. W.H. Freeman and Company, New York.

NIST/SEMATECH. 2015. e-Handbook of Statistical Methods. NIST, Dept. of Commerce, Washington, DC. http://www.itl.nist.gov/div898/handbook/ (accessed 22 Apr. 2016).

PRISM Climate Group. 2014. Northwest Alliance for Computational Science and Engineering. Oregon State University. http://prism.oregonstate.edu (accessed 17 Feb. 2016).

R Core Team. 2013. R Foundation for Statistical Computing. R Foundation, Vienna, Austria. http://www.R-project.org/ (accessed 22 Apr. 2016).

Rice, P., and B. Horgan. 2010. Nutrient loss in runoff from turf: Effect on surface water quality. USGA Turfgrass and Environmental Research Online 9 (1):1–10. http://usgatero.msu.edu/tero_browse.html#2010 (accessed 22 Apr. 2016).

Stowell, L., and M. Woods. 2013. Minimum levels for sustainable nutrition (MLSN). Appl. Turfgrass Sci. doi: 10.2134/ATS-2013-0008BC

Throssell, C.S., G.T. Lyman, M.E. Johnson, G.A. Stacey, and C.D. Brown. 2009a. Golf course environmental profile measures nutrient use and management and fertilizer restrictions, storage and equipment calibration. Appl. Turfgrass Sci. doi:10.1094/ATS-2009-1203-01-RS

Throssell, C.S., G.T. Lyman, M.E. Johnson, G.A. Stacey, and C.D. Brown. 2009b. Golf course environmental profile measures water use, source, cost, quality, and management and conservation strategies. Appl. Turfgrass Sci. doi:10.1094/ATS-2009-0129-01-RS

USDA Economic Research Service (ERS). 2013. Average US farm prices of selected fertilizers, 1960–2013. http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26727 (accessed 31 Oct. 2015).

Warnes, G.R., B. Bolker, T. Lumley, and R.C. Johnson, 2015. Various R programming tools for model fitting. http://www.sf.net/projects/r-gregmisc (accessed 26 Apr. 2016).

Yee, T.W. 2014. Package “VGAM.” http://cran.r-project.org/web/packages/VGAM/VGAM.pdf (accessed 22 Apr. 2016).