Nutrient Use and Management Practices on United States Golf Courses

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Abstract. **Nutrient use on United States golf courses increases management costs and has the potential to influence ecosystems. Therefore, it is critical to assess nutrient use and management practices to develop and teach best management practices. The objectives of this survey were to measure nutrient use and management practices on United States golf courses in 2021, and to determine if changes occurred since 2006. A survey was developed and distributed via e-mail to 14,033 United States golf facilities, with 1444 responding. From 2006 to 2021, the total projected nitrogen (N), available phosphorus (P_2O_5), and soluble potash (K_2O) applied declined by 41%, 59%, and 54%, to 54,376, 13,761, and 41,386 tons, respectively. These reductions were attributed to course closures, reduced fertilized acres, reduced application rates, and nutrient use restrictions. The percentage of facilities that did not apply P_2O_5 increased to 21%, which is likely a result of P_2O_5 application restrictions. Soil testing was associated with greater application rates of N, P_2O_5, and K_2O. Returning clippings, using precision fertilizer applications, reducing turfgrass acreage, and considering N release from soil organic matter were associated with reduced application rates of P_2O_5. Golf course superintendents have contributed to nationwide reductions in N, P_2O_5, and K_2O, as evidenced by the reduction in fertilized acres and the reduction in nutrient use rates from 2006 to 2021.**

In 2021, an estimated 106 million Americans were involved with the game of golf by playing, watching, reading, or listening to a golf-related source (National Golf Foundation 2021). Therefore, golf is an important part of American culture. The turfgrass that golf is played on is unique relative to other turfgrasses because it is subjected to high expectations and recurring traffic that requires sustained vigor. These expectations and recuperative needs generally are not achieved without supplemental nutrient applications. Some applied nutrients, such as nitrogen (N) and phosphorus (P), are potential elements of environmental impairment and can have negative consequences on ecosystems.

In 2006, Throssell et al. (2009) surveyed 16,386 golf facilities, with a 15.6% response rate. A total of 101,096 tons of N were applied to 1.3 million acres, 36,810 tons of available phosphorus (P_2O_5) were applied to 1.1 million acres, and 99,005 tons of soluble potash (K_2O) were applied to 1.2 million acres. Generally, the average rates of N, P_2O_5, and K_2O were greater on putting greens than on any other course feature. The most common factors that golf facilities used to determine their decisions about applying nutrients were visual observations, previous product performance, and soil analysis. Throssell et al. (2009) provided a baseline from which future change could be measured.

In 2015, Gelernter et al. (2016) conducted the second assessment of nutrient use on United States golf courses, with a total of 1529 facilities returning a completed survey, accounting for 10% of known facilities. They reported that N, P_2O_5, and K_2O usage declined to 61,214, 15,760, and 51,705 tons, respectively. That study also found that the percentage of golf facilities that applied P_2O_5 had declined to 80% from 2006 to 2014. Legislated P_2O_5 restrictions began before the Throssell et al. (2009) study (Rosen and Horgan 2005), but they have increased since 2005. Regulations regarding P_2O_5 applied to turfgrass may include limiting the total amount applied, the time of year, or complete elimination of P_2O_5 in turfgrass fertilizer (Carey et al. 2012). Regulations have been implemented in numerous states and are not insolated to any specific region. It is likely that the increased restrictions on P_2O_5 applications resulted in fewer facilities applying P_2O_5 and, concomitantly, a reduction in P_2O_5 applied overall. Gelernter et al. (2016) reported that nutrient application rates were the primary factor behind projected N and K_2O reductions, whereas reduction of fertilized acres were more influential on projected P_2O_5 reduction. Gelernter et al. (2016) also reported golf facilities that conducted soil tests on putting greens applied 1.1-fold, 1.5-fold, and 1.6-fold more N, P_2O_5, and K_2O, respectively, than golf facilities that did not test the soil. This result appears contrary to the notion that soil testing is a conservation practice.

Throssell et al. (2009) provided a baseline to measure nutrient change. Gelernter et al. (2016) provided the first assessment of nutrient change. It is essential to continue to assess nutri-

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.0929	ft^2	m^2	10.7639
48.8243	lb/1000 ft^2	$kg \cdot ha^{-1}$	0.0205
1	ppm	$mg \cdot kg^{-1}$	1
0.9072	ton(s)	Mg	1.1023

ent usage and management practices on United States golf facilities. Therefore, the objective of this survey was to measure the change in nutrient use and frequency of management practices used on United States golf facilities from 2006 to 2021.

Materials and methods

A survey instrument including identical questions to those used by Gelernter et al. (2016) was created; it allowed responses to be compared across years. Respondents were asked to provide nutrient data according to the guaranteed analysis of the fertilizer label (Association of American Plant Food Control Officials 2017). Therefore, N, P, and potassium were reported as N, P_2O_5, and K_2O. The instrument was distributed in English via online software (Qualtrics, Provo, UT). A survey link was emailed to golf facilities using the mailing lists of the National Golf Foundation (Jupiter, FL) and the Golf Course Superintendents Association of America (Lawrence, KS), which resulted in the link being sent to 14,033 unique golf facilities. A golf facility was defined as a business where golf could be played on one or more golf courses. Additionally, the survey and the link were promoted on social media by Golf Course Superintendents Association of America staff. The survey was available for completion for 7 consecutive weeks beginning on 1 Apr 2022. Four e-mail reminders were sent to encourage survey participation as well as survey completion by respondents who had started but had not completed the survey. Respondents remained anonymous within the data file by omitting their names and using an assigned unique identification number. One response was allowed per golf course. Data were merged with data from the same survey conducted in 2006 and 2014 to allow for the measurement of change over time. Responses were received from 1444 facilities, which represented 10.3% of the known total of United States golf facilities.

Respondents were stratified by agronomic region (Fig. 1). To provide a valid representation of United States golf courses, data were weighted. Responses were categorized into one of 35 categories depending on the facility type (public or private), number of holes (9, 18, or ≥27), and public green fee (<$55 or ≥$55 per round) (Supplemental Table S1). The weights were calculated by determining the proportion of each group within the total survey response.

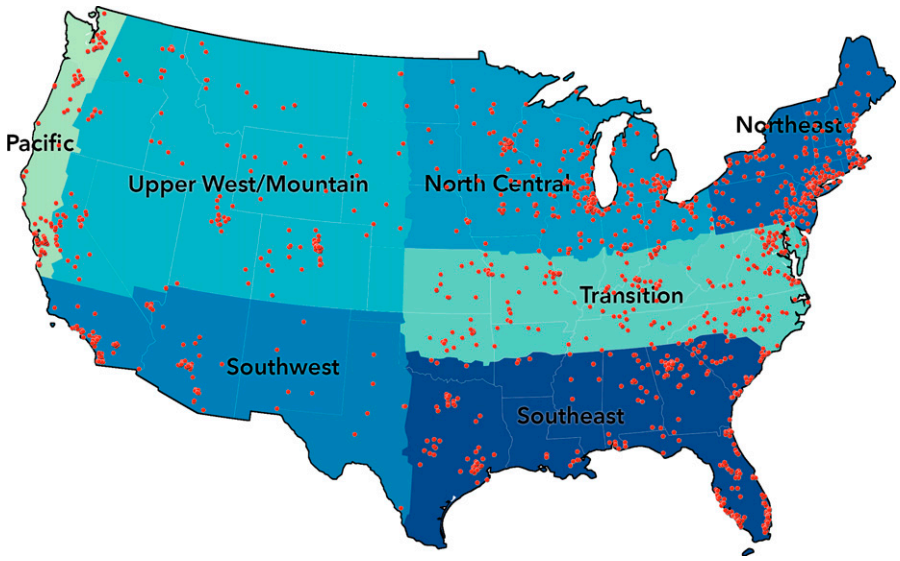

Fig. 1. Distribution of the 2022 survey and seven agronomic regions.

Data residuals were analyzed both graphically and numerically and identified the data as non-normally distributed (National Institute of Standards and Technology 2012). As a result, data were fit to a log-logistic model. Median separations were performed using the Tukey-Kramer test (α = 0.1). Projected applied nutrients were determined by multiplying the number of golf facilities by the percentage that applied nutrients on a given course feature, and then multiplying that value by the average amount of nutrient applied. Projected fertilized acres were determined by dividing the total pounds of nutrients applied by the average pounds per 1000 ft^2 and then converting to acres. Mean separations were not conducted for projected values. Golf facility frequencies were calculated using PROC SURVEYfreq in SAS (version 9.4; SAS Institute Inc., Cary, NC). To determine if survey responses changed over time, years were paired. Differences among all-pairwise comparisons were determined using the chi-square test at the 10% significance level.

Results and discussion

Total projected N, P_2O_5, and K_2O on United States golf facilities declined by 41%, 59%, and 54% from 2006 to 2021, respectively (Fig. 2A), and similar declines were measured within each region (Table 1). Reductions in projected applications of N, P_2O_5, and K_2O differed across regions. Nationally, N reductions ranged from 34% to 46% in the Pacific and Southwest, respectively. Nationally, P_2O_5 reductions ranged from 40% to 73% in the Southwest and North Central, respectively, and K_2O was reduced by 49% to 62% in the Northeast and North Central, respectively. These reductions are likely a result of several factors. First, golf facility closures continue to outpace facility openings, resulting in a net reduction of golf facilities from 2006 to 2021, both nationally and regionally (Table 2). Second, nutrient application rates at operational golf facilities declined. The nutrient application rate is perhaps the most effective measurement of efficient nutrient usage because it is unaffected by facility closures. The national medians of N, P_2O_5, and K_2O applied per 1000 ft^2 per golf facility declined from 2006 to 2021 by 30%, 63%, and 42% to 1.6, 0.3, and 1.1 lb/1000 ft^2, respectively (Fig. 2C). The last factor that likely influenced the total projected applied nutrients is the number of acres fertilized with N, P_2O_5, and K_2O, which declined by 25%, 53%, and 32%, respectively, from 2006 to 2021 (Table 3). Nationally, the greatest decrease occurred with P_2O_5; fertilized acres declined by ~530,000 acres from 2006 to 2021. Reductions in fertilized acres within regions also

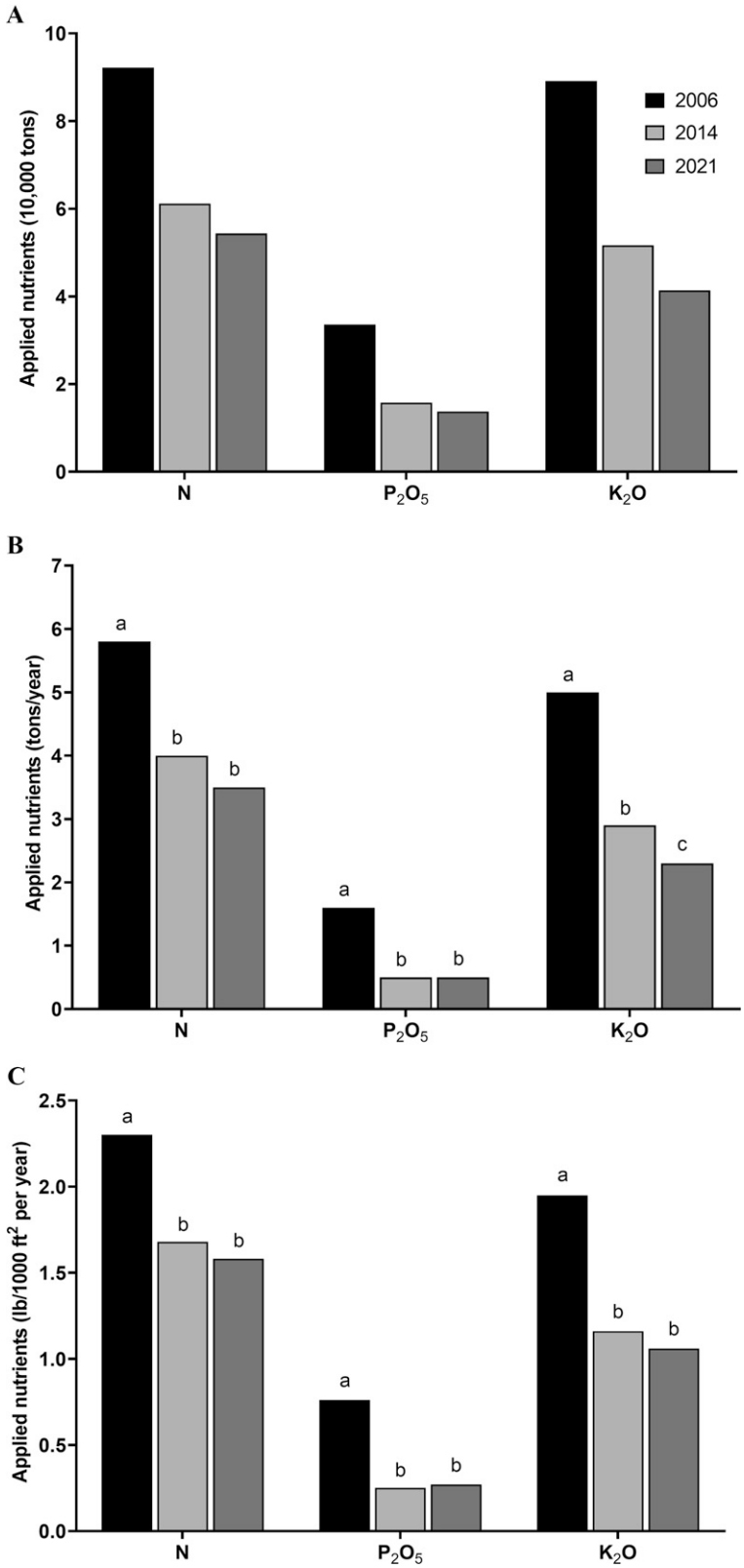

Fig. 2. Nutrient use among United States golf facilities as (A) total projected applied nutrients, (B) median applied nutrients per golf facility, and (C) median applied nutrients per acre per golf facility in 2006, 2014, and 2021. Statistical separation of projected applied nutrients was not conducted. Bars with a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level. 1 ton = 0.9072 Mg. 1 lb/1000 ft^2 = 48.8243 kg·ha^{-1}.

varied. Changes in acres fertilized with N ranged from 21% to 37% in the Upper West Mountain and Southwest, respectively. Reductions in acres fertilized with P_2O_5 were more variable and ranged from 31% to 70% in the Upper West Mountain and North Central, respectively. Fewer acres were fertilized with K_2O, and reductions ranged from 28% in the Upper West Mountain and Southeast to 40% in the Southwest. Therefore, we postulated that reductions in facility closures, application rates, and fertilized acres account for the reduction of total nutrients applied from 2006 to 2021.

Nationally, the median fertilized acres declined by 16.3 acres (13.5%) from 2006 to 2021, which is the result of fertilized acreage reductions in the Pacific, Southeast, Southwest, and Transition of 36%, 18%, 40%, and 14%, respectively (Table 4). Nationally and within each region, the greatest median fertilized acres were roughs, followed by fairways and natural areas. Pooled across the United States, fertilized rough acreage remained unchanged from 2006 to 2021. Fertilized acres of natural areas, greens, and tees increased by 25%, 13%, and 9%, respectively, from 2006 to 2021. Fertilized acres of fairways, practice areas, and grounds decreased by 9%, 27%, and 35%, respectively, from 2006 to 2021. From 2006 to 2021, in all regions of the United States (except Pacific), fertilized acres were reduced (25%–44%) in the nonplay area denoted as "grounds." Golf facilities interested in reducing fertilized acres may consider reducing fertilization of out-of-play roughs and natural areas, which may further contribute to an overall reduction of applied nutrients and potentially result in improved efficiencies, reduced environmental risk, and reduced maintenance costs.

The N application rates declined nationally on each course feature except natural areas, which received the lowest N rate of any course feature (Table 5). Nationally, N rates declined between 18% and 28% from 2006 to 2021, depending on the course feature. The N rate reductions (total) were reported within each region except the Northeast and Pacific, where the applied N in 2021 was equivalent to that in 2006. Generally, N rate reductions were reported for most course features within most regions. The N rates on putting

Table 1. Projected nitrogen (N), available phosphorus (P_2O_5), and soluble potash (K_2O) applied to golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

Region (Fig. 1)	2006	2014	2021	Change 2006–21
	(tons)[i]			(%)
		N		
United States	92,185	61,215	54,376	−41.0
North Central	15,047	10,612	8,711	−42.1
Northeast	9,139	6,560	5,656	−38.1
Pacific	3,110	2,124	2,052	−34.0
Southeast	32,532	18,894	19,302	−40.7
Southwest	13,247	8,986	7,209	−45.6
Transition	13,600	9,688	7,982	−41.3
Upper West/Mountain	5,510	4,350	3,466	−37.1
		P_2O_5		
United States	33,626	15,759	13,761	−59.1
North Central	4,657	1,421	1,242	−73.3
Northeast	3,483	1,152	1,351	−61.2
Pacific	1,123	966	444	−60.5
Southeast	11,114	5,144	4,780	−57.0
Southwest	5,408	3,053	3,254	−39.8
Transition	5,876	3,064	1,924	−67.3
Upper West/Mountain	1,965	960	766	−61.0
		K_2O		
United States	89,124	51,705	41,386	−53.6
North Central	11,960	7,142	4,496	−62.4
Northeast	8,090	4,719	4,145	−48.8
Pacific	2,697	1,949	1,188	−55.9
Southeast	37,246	20,478	18,362	−50.7
Southwest	12,127	6,397	4,733	−61.0
Transition	12,670	8,354	6,383	−49.6
Upper West/Mountain	4,334	2,666	2,079	−52.0

[i] 1 ton = 0.9072 Mg.

greens were reduced in all agronomic regions and ranged from 24% to 31%. Similarly, the N rate reduction on tees ranged from 15% in the Upper West/Mountain to 31% in the Northeast and Southeast. Similarly, fairway N rates were reduced in all regions except the Southwest, and they ranged from 14% to 32% in the Upper West/Mountain and Northeast, respectively. The N rate reductions on golf course roughs were reported in all regions except the Southwest. A reduction of applied N results in less N available for plant uptake, but, depending on many factors, including turfgrass type, soil, and environmental conditions, it may not necessarily result in a reduction of turfgrass quality (Tang 2018). Recent research has shown that N rates that were previously recommended may exceed the minimum necessary to result in acceptable turfgrass (McGroary et al. 2017). Therefore, the reduced N rates measured during the current study are consistent with current evidence and may result in reduced environmental risk (Shaddox et al. 2016b) and maintenance costs without measurable loss of turfgrass quality.

Table 2. Number of golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021 and the resulting projected change in nutrient use.

	Golf facilities			Projected nutrient applied[i]		
Region	2006	2014	2021	N	P_2O_5	K_2O
	(no.)			Change 2006–21 (tons)		
United States	15,990	15,372	14,033	−5,027	−1,536	−3,952
North Central	4,123	3,920	3,555	−1,005	−130	−549
Northeast	2,739	2,690	2,470	−387	−117	−324
Pacific	629	615	565	−181	−51	−126
Southeast	3,216	3,020	2,737	−2,056	−694	−1,953
Southwest	1,221	1,208	1,138	−352	−216	−221
Transition	2,951	2,793	2,509	−975	−315	−735
Upper West/Mountain	1,111	1,125	1,059	−70	−13	−43

[i] Determined by multiplying the change in golf facilities from 2006 to 2021 by the average amount of N, P_2O_5, or K_2O applied. 1 ton = 0.9072 Mg.

Table 3. Projected acres fertilized with nitrogen (N), available phosphorus (P_2O_5), and soluble potash (K_2O) on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

Region	2006	2014	2021	Change 2006–21
	Area (acres)[i]			(%)
		N		
United States	1,179,055	986,063	889,378	−24.6
North Central	279,185	230,025	206,284	−26.1
Northeast	161,846	134,774	125,551	−22.4
Pacific	42,969	34,707	33,458	−22.1
Southeast	280,685	234,015	213,414	−24.0
Southwest	118,683	93,383	80,850	−31.9
Transition	210,663	178,741	162,981	−22.6
Upper West/Mountain	85,023	80,419	66,840	−21.4
		P_2O_5		
United States	1,004,391	540,581	472,923	−52.9
North Central	222,890	87,951	66,723	−70.1
Northeast	143,916	57,360	50,298	−65.1
Pacific	41,553	27,546	20,789	−50.0
Southeast	237,648	138,002	134,054	−43.6
Southwest	99,658	75,983	63,323	−36.5
Transition	189,959	101,034	89,916	−52.7
Upper West/Mountain	68,766	52,704	47,819	−30.5
		K_2O		
United States	1,126,967	874,534	767,883	−31.9
North Central	264,087	199,216	166,854	−36.8
Northeast	157,981	121,645	110,601	−30.0
Pacific	42,467	31,495	28,117	−33.8
Southeast	268,337	219,974	194,550	−27.5
Southwest	113,167	81,642	67,637	−40.2
Transition	204,407	155,772	144,707	−29.2
Upper West/Mountain	76,520	64,791	55,417	−27.6

[i] 1 acre = 0.4047 ha.

Similar to N rates, P_2O_5 and K_2O application rates declined nationally from 2006 to 2021 by 63% and 42%, respectively, and within each region except the Pacific (Tables 6 and 7). Nationally and regionally, the greatest P_2O_5 and K_2O application rates were reported for putting greens and grounds. Reductions in P_2O_5 application rates have not changed from 2006 to 2021 for roughs, practice areas, and natural areas in four of the seven regions. A three-fold increase in the P_2O_5 application rate was reported for natural areas in the Northeast. Determining the cause of this increase was beyond the scope of this study; therefore, it remains unknown. With few exceptions, the applied K_2O reduction ranged from 23% to 50% for all course features in all regions, except in natural areas where no changes were reported. The Southwest was the only region that did not report reductions in K_2O application rates on fairways, roughs, and grounds. Putting greens are unique areas relative to other golf facility features because they receive the majority of foot traffic (Moeller and Petrovsky 2022) and are often constructed primarily with sand (United States Golf Association 2018). Foot traffic often results in turfgrass damage, which may require additional nutrients to aid recovery (Nikolai et al. 2021). Additionally, sands are prone to poor moisture and nutrient retention, which can result in the need to apply more P_2O_5 and K_2O on those areas than on other areas of the golf facility where turfgrass is grown on fine-textured, native soils. Therefore, we postulated that the combination of foot traffic and sand root zones resulted in increased rates of P_2O_5 and K_2O on putting greens relative to other course features.

Similar to the projected nutrients applied, the national medians of N, P_2O_5, and K_2O applied per golf facility declined by 40%, 69%, and 54% from 2006 to 2021, respectively (Fig. 2). The median K_2O applied per golf facility also declined from 2014 to 2021. The median N use reductions ranged from 31% to 84% from the North Central to Southwest, respectively, and were also measured within each region, except in the Northeast and Pacific, where the median N use was equivalent to 2006 (Table 8). Available P (tons/year per facility) reductions ranged from 46% to 72% in the Northeast and Transition, respectively, and K_2O reductions ranged from 31% in the Northeast to 71% in the Southwest.

The N rates applied per 1000 ft^2 on 18-hole and ≥27-hole facilities were 1.95 and 1.67 lb/1000 ft^2, respectively, which were greater than the 1.11 lb/1000 ft^2 applied to nine-hole facilities. However, the P_2O_5 rate reported for ≥27-hole facilities was 0.17 lb/1000 ft^2, which was equivalent to the 0.24 and 0.29 lb/1000 ft^2 applied on nine-hole and 18-hole facilities, respectively. Similarly, 1.20 lb/1000 ft^2 of K_2O was applied on ≥27-hole facilities, which was equivalent to the 0.74 and 1.14 lb/1000 ft^2 applied on nine-hole and 18-hole facilities, respectively. The N

Table 4. Median fertilized acres on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

Yr	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
	Area (acres)[ii]							
	Total							
2006	120.4 a[iii]	125.2 a	88.6 a	123.7 a	130.8 a	148.4 a	119.9 a	124.2 a
2014	114.3 a	107.0 b	106.4 a	125.3 ab	107.3 b	171.1 a	124.2 a	137.5 a
2021	104.1 b	117.8 ab	90.1 a	79.2 b	107.7 b	89.6 b	103.5 b	115.1 a
	Roughs							
2006	40.8 a	45. 4a	33.0 a	31.0 ab	42.3 a	41.1 a	45.4 ab	35.9 a
2014	38.8 a	38. 8b	28.9 a	45.2 a	41.6 a	47.8 a	41.6 b	35.4 a
2021	40.6 a	42.7 ab	29.5 a	26.7 b	47.1 a	40.6 a	47.7 a	32.0 a
	Fairways							
2006	25.6 a	23.6 a	21.3 a	27.8 a	31.2 a	31.1 a	24.8 a	26.5 a
2014	23.8 b	21.9 ab	21.3 a	26.1 a	27.1 b	31.5 a	21.8 b	27.0 a
2021	23.4 b	20.9 b	21.3 a	26.6 a	27.5 b	28.4 a	22.9 ab	22.9 a
	Natural areas							
2006	13.9 b	13.4 b	9.6 a	17.8 a	15.0 a	29.2 a	12.4 b	18.6 a
2014	12.2 b	13.6 b	9.8 a	11.7 a	10.9 a	31.3 a	9.2 b	25.2 a
2021	17.3 a	26.9 a	14.2 a	8.9 a	16.0 a	16.7 a	17.5 a	17.5 a
	Practice areas							
2006	4.9 a	4.0 a	3.6 a	4.0 a	6.1 a	5.1 ab	5.6 a	5.5 a
2014	4.6 a	4.0 a	3.1 ab	4.0 a	5.0 b	6.4 a	5.8 a	4.8 ab
2021	3.6 b	2.1 b	2.7 b	3.1 a	5.3 ab	4.5 b	3.8 b	4.0 b
	Greens							
2006	2.4 b	2.4 b	2.5 b	2.2 a	2.7 a	2.3 b	2.5 ab	1.9 b
2014	2.5 b	2.6 a	2.6 ab	2.5 a	2.6 a	2.8 a	2.4 b	2.2 ab
2021	2.7 a	2.6 ab	2.8 a	2.4 a	2.8 a	2.7 a	2.7 a	2.3 a
	Tees							
2006	2.2 b	2.0 a	1.9 b	1.8 a	3.0 a	2.3 b	2.3 b	1.7 a
2014	2.3 ab	2.2 a	2.0 ab	2.2 a	2.7 b	3.1 a	2.3 b	1.9 a
2021	2.4 a	2.1 a	2.1 a	2.0 a	3.0 a	2.7 a	2.6 a	2.0 a
	Grounds							
2006	1.7 a	1.6 a	1.7 a	1.0 a	2.0 a	1.6 a	1.7 a	1.5 a
2014	1.4 b	1.4 a	1.4 ab	1.5 a	1.4 b	1.2 ab	1.4 ab	1.2 ab
2021	1.1 c	0.9 b	1.2 b	0.8 a	1.5 b	0.9 b	1.1 b	0.9 b

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.
[ii] 1 acre = 0.4047 ha.
[iii] Within columns, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.

and K_2O rates on private golf facilities were 1.81 and 1.28 lb/1000 ft^2, respectively; these were greater than the 1.44 and 0.93 lb/1000 ft^2 of N and K_2O applied to public facilities. Equivalent rates of P_2O_5 were applied on public and private facilities: 0.25 and 0.29 lb/1000 ft^2, respectively. The increased N rates on ≥27-hole facilities are likely a result of those facilities operating with larger budgets and possibly the result of golfers expecting greater quality turfgrass on larger facilities. This postulate is consistent with the difference between public and private facilities resulting from the fact that private facilities operate with larger fertilizer budgets than public facilities (Golf Course Superintendents Association of America 2021b).

The percentage of golf facilities that applied N to greens, tees, fairways, roughs, and natural areas declined from 2006 to 2021 (Table 9). However, the percentage of facilities that applied N to greens, tees, and fairways remained more than 93%. Conversely, the 11% and 53% reductions from 2006 to 2021 at facilities applying N to roughs and natural areas, respectively, are of consequence because the magnitude of reduction and the number of acres fertilized likely led to a significant reduction in the total N applied. The percentage of facilities that applied P_2O_5 on United States golf facilities declined on each course feature from 2006 to 2021. In 2006, 92% of golf facilities applied P_2O_5 to greens; however, in 2021, that percentage declined to 75%. Perhaps the most impactful change occurred on fairways and roughs, where the percentage of golf facilities applying P_2O_5 declined by nearly half from 2006 to 2021. This reduction is likely a result of existing restrictions on the use of P_2O_5 on turfgrass. Restrictions may include banning the sale or use of phosphorus applied to turfgrass. This reduction may be viewed as beneficial and will not likely result in a reduction in turfgrass quality unless soil test levels decline below a critical *P* value. Critical soil *P* values vary according to numerous variables, including but not limited to soil type, soil texture, turfgrass species, turfgrass maturity, and they may range

Table 5. Nitrogen (N) use rates on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

Yr	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
	N (lb/1000 ft^2 per yr)[ii]							
	Total							
2006	2.3 a[iii]	1.8 a	1.9 a	2.3 a	3.6 a	3.8 a	2.0 a	2.3 a
2014	1.7 b	1.3 b	1.6 a	1.7 a	2.7 b	2.5 ab	1.6 b	1.7 ab
2021	1.6 b	1.4 b	1.5 a	2.4 a	2.2 b	1.1 b	1.4 b	1.3 b
	Greens							
2006	4.3 a	3.4 a	3.6 a	5.1 a	7.7 a	5.1 a	4.2 a	3.9 a
2014	3.8 b	2.8 b	3.2 b	4.0 b	5.9 b	5.1 a	4.0 a	3.5 b
2021	3.1 c	2.4 c	2.5 c	3.8 b	5.5 b	3.8 b	3.2 b	2.8 c
	Tees							
2006	3.9 a	3.4 a	3.6 a	4.6 a	5.8 a	4.9 a	3.4 a	3.4 a
2014	3.1 b	2.7 b	3.0 b	3.5 b	4.1 b	4.8 a	2.7 b	2.9 b
2021	2.9 c	2.6 b	2.5 c	3.9 ab	4.0 b	4.0 b	2.5 c	2.9 b
	Fairways							
2006	3.1 a	2.7 a	2.8 a	3.4 a	4.5 a	4.1 a	2.9 a	2.8 a
2014	2.6 b	2.1 b	2.3 b	2.8 ab	3.5 b	4.2 a	2.6 b	2.4 b
2021	2.4 c	2.0 b	1.9 c	2.7 b	3.5 b	3.7 a	2.3 c	2.4 b
	Roughs							
2006	2.4 a	1.7 a	1.9 a	2.6 a	4.0 a	3.2 a	2.1 a	2.3 a
2014	1.9 b	1.4 b	1.5 b	1.9 b	2.7 b	3.3 a	1.7 b	1.9 b
2021	1.8 b	1.3 b	1.4 b	2.0 b	2.6 b	2.8 a	1.7 b	2.1 ab
	Practice areas							
2006	3.3 a	2.7 a	2.6 a	3.2 a	5.1 a	4.4 a	3.0 a	2.9 a
2014	2.8 b	2.5 ab	2.2 b	2.8 a	3.6 b	4.6 a	2.5 b	2.6 ab
2021	2.7 b	2.3 b	2.1 b	2.8 a	3.8 b	3.1 b	2.5 b	2.4 b
	Natural areas							
2006	1.3 a	1.2 a	1.0 a	1.1 a	1.4 a	2.2 a	1.3 a	1.2 a
2014	1.1 b	0.8 ab	0.7 a	1.0 a	1.3 a	1.6 a	0.9 b	1.4 a
2021	1.0 ab	0.7 b	1.2 a	1.1 a	1.4 a	1.4 a	0.9 ab	0.8 a
	Grounds							
2006	2.6 a	2.3 a	2.2 a	3.4 a	3.8 a	3.1 ab	2.4 a	2.5 a
2014	2.2 b	2.0 b	1.9 b	2.9 a	2.8 b	3.8 a	1.8 b	2.4 a
2021	2.0 c	1.8 c	1.8 b	2.8 a	2.5 b	2.7 b	1.9 b	2.1 a

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.
[ii] 1 lb/1000 ft^2 = 48.8243 kg·ha^{-1}.
[iii] Within columns, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.

from as low as 1.4 ppm to as high as 63.6 ppm, depending on the extractant used (Guillard and Dest 2003). Using one soil extractant for all soils is unsound. Therefore, establishing a single critical soil *P* value for all soils is also unsound. However, the Mehlich-3 extractant was the most common evidence-based extractant used for P analysis on United States golf facilities in 2021 (Table 10). Critical Mehlich-3 *P* values as low as 5 ppm have been reported for cool-season turfgrasses (Kreuser et al. 2012), and *P* values more than 10 ppm have been reported for warm-season turfgrasses (Liu et al. 2008) [converted from Mehlich-I *P* values according to Mylavarapu et al. (2020)]. Therefore, golf facilities may reduce or potentially eliminate P_2O_5 applications with little concern for turfgrass quality as long as the soil Mehlich-3 P concentration is greater than the critical minimum, which is likely between 5 and 20 ppm for established turfgrass. The percentage of turfgrass grown on P-deficient soils is unknown. A soil survey documenting the soil P concentration of turfgrass swards by location and course feature (i.e., putting greens, tees, fairways) would provide valuable information to golf course superintendents and help determine the risk of encountering P-deficient soils.

The percentage of golf facilities that reported no applications of N to any course feature was less than 1% and was equivalent to that in 2006 (Fig. 3). However, the percentage of facilities that reported no applications of P_2O_5 or K_2O increased from 2006 to 2021 to 21% and 6%, respectively. The increased percentage of facilities that are not applying P_2O_5 is likely a result of federal, state, tribal, or local nutrient restrictions. The percentage of golf facilities that operated within P_2O_5 restrictions increased from 5% to 15% from 2006 to 2021 (data not shown). Additionally, in 2021, the P_2O_5 application rate on golf facilities that operated within P_2O_5 restrictions was 0.09 lb/1000 ft^2; however, it was 0.32 lb/1000 ft^2 on facilities that did not operate within P_2O_5 restrictions. Less than 4% of facilities were subjected

Table 6. Available phosphorus (P_2O_5) use rates on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

Yr	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
	P_2O_5 (lb/1000 ft^2 per yr)[ii]							
	Total							
2006	0.8 a[iii]	0.6 a	0.7 a	1.0 a	0.9 a	2.1 a	0.9 a	0.9 a
2014	0.2 b	0.1 b	0.2 b	0.4 a	0.8 ab	0.6 b	0.3 b	0.4 b
2021	0.3 b	0.1 b	0.4 b	0.6 a	0.5 b	0.9 b	0.3 b	0.3 b
	Greens							
2006	1.5 a	1.0 a	1.2 a	1.7 a	2.2 a	2.1 a	1.6 a	1.3 a
2014	1.1 b	0.7 b	0.8 b	1.1 b	1.7 b	1.8 a	1.4 b	0.9 b
2021	1.0 c	0.6 b	0.8 b	1.0 b	1.8 b	1.7 a	1.0 c	0.7 c
	Tees							
2006	1.3 a	1.0 a	1.3 a	1.4 a	1.7 a	1.8 a	1.3 a	1.0 a
2014	1.0 b	0.7 b	0.9 b	1.1 a	1.3 b	1.5 a	1.0 b	0.8 b
2021	0.9 b	0.6 b	0.8 b	1.2 a	1.4 b	1.7 a	0.9 b	0.6 c
	Fairways							
2006	1.1 a	0.8 a	0.9 a	1.0 a	1.5 a	1.6 a	1.1 a	0.9 a
2014	0.9 b	0.5 b	0.6 b	0.9 a	1.2 b	1.4 a	1.0 a	0.7 ab
2021	0.8 b	0.5 b	0.7 b	0.9 a	1.2 b	1.6 a	0.7 b	0.5 b
	Roughs							
2006	0.9 a	0.5 a	0.7 a	0.8 a	1.4 a	1.5 a	0.9 a	0.8 a
2014	0.8 b	0.4 b	0.5 b	0.6 a	1.2 ab	1.3 a	0.8 ab	0.7 ab
2021	0.8 b	0.4 ab	0.7 ab	0.6 a	1.1 b	1.3 a	0.6 b	0.5 b
	Practice areas							
2006	1.2 a	0.8 a	1.0 a	1.0 a	1.6 a	1.8 a	1.2 a	1.0 a
2014	1.0 b	0.8 a	0.6 b	0.9 a	1.1 b	1.6 a	1.0 b	0.8 ab
2021	1.0 b	0.9 a	1.0 a	0.9 a	1.3 ab	1.4 a	0.9 b	0.6 b
	Natural areas							
2006	0.8 a	0.7 a	0.6 b	1.1 a	1.1 a	1.3 a	0.7 a	0.4 a
2014	0.7 a	0.0[iv]	0.5 ab	0.8 ab	0.6 a	1.1 a	0.6 a	0.6 a
2021	0.7 a	0.3 a	1.8 a	0.4 b	0.7 a	1.5 a	0.8 a	0.3 a
	Grounds							
2006	2.6 a	2.3 a	2.2 a	3.4 a	3.8 a	3.1 ab	2.4 a	2.5 a
2014	2.2 b	2.0 b	1.9 b	2.9 a	2.8 b	3.8 a	1.8 b	2.4 a
2021	2.0 c	1.8 c	1.8 b	2.8 a	2.5 b	2.7 b	1.9 b	2.1 a

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.
[ii] 1 lb/1000 ft^2 = 48.8243 kg·ha^{-1}.
[iii] Within columns, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.
[iv] Values without variability were not analyzed.

to N or K_2O restrictions, and no differences were measured between the rates of N and K_2O applied on facilities subjected or not subjected to nutrient restrictions (data not shown). Therefore, legislated restrictions on P_2O_5 applications appear to have resulted in reduced amounts of P_2O_5 applied, and they have likely increased the percentage of golf facilities that omitted P_2O_5 applications altogether.

Golf facilities that conduct soil tests applied more N and K_2O to each course feature in 2021, except natural areas (Fig. 4), which was consistent with the results reported by Gelernter et al. (2016). Soil testing was less associated with P_2O_5 because greater rates of P_2O_5 were applied only to practice areas and roughs on facilities that conducted soil tests than on facilities that did not. The reduced association with P_2O_5 may be a result of the overall reduction in P_2O_5 applied nationally and regionally. With fewer facilities applying P_2O_5 and less P_2O_5 applied overall, the association of soil testing with applied P_2O_5 may have been concomitantly reduced. This study could not determine whether soil testing resulted in greater N rates; it could only determine that there is a significant relationship between the two. Potential environmental impairment can occur with N, and excessive N may increase environmental risk (Shaddox et al. 2016a) and management costs (Shaddox and Unruh 2021). Traditional soil tests that use chemical extractants have not been correlated or calibrated with N. Additionally, N soil test results may vary greatly because of the rapid fluctuation of N in soils (Carrow et al. 2001). Therefore, N soil tests are considered unreliable and should not be used to make decisions regarding N fertilizer (Reicher and Throssell 1998). Although some experimental N test methods are undergoing study (Moore et al. 2019), none are sufficiently widely used to make N fertilizer recommendations. Therefore, these

Table 7. Soluble potash (K_2O) use rates on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
Yr	K_2O (lb/1000 ft^2 per yr)[ii]							
	Total							
2006	1.9 a[iii]	1.4 a	1.6 a	1.9 a	3.3 a	3.2 a	1.9 a	1.8 a
2014	1.2 b	0.7 b	1.1 b	1.2 a	2.7 ab	1.2 b	1.2 b	1.1 ab
2021	1.1 b	0.6 b	1.1 b	1.3 a	1.9 b	1.5 b	0.8 c	0.6 b
	Greens							
2006	4.5 a	3.4 a	3.4 a	4.6 a	9.9 a	6.6 a	4.3 a	3.2 a
2014	3.6 b	2.4 b	2.7 b	3.2 b	7.8 b	5.0 b	4.2 a	3.0 a
2021	2.9 c	1.9 c	2.1 c	3.1 b	6.8 c	3.5 c	3.1 b	2.2 b
	Tees							
2006	3.3 a	2.8 a	3.1 a	3.6 a	5.8 a	4.0 a	2.9 a	2.2 a
2014	2.4 b	2.0 b	2.2 b	2.6 b	3.8 b	3.4 ab	2.3 b	2.0 ab
2021	2.0 c	1.6 c	1.6 c	2.3 b	3.8 b	2.9 b	1.8 c	1.7 b
	Fairways							
2006	2.6 a	2.1 a	2.3 a	2.6 a	4.6 a	3.0 a	2.5 a	1.9 a
2014	1.9 b	1.4 b	1.5 b	2.0 ab	3.3 b	2.8 a	2.0 b	1.6 ab
2021	1.6 c	1.1 c	1.3 c	1.7 b	3.1 b	2.4 a	1.6 c	1.4 b
	Roughs							
2006	1.9 a	1.2 a	1.5 a	2.0 a	4.1 a	2.3 a	1.8 a	1.7 a
2014	1.5 b	0.8 b	1.1 b	1.3 b	2.7 b	2.2 a	1.5 b	1.3 b
2021	1.2 c	0.6 c	0.9 b	1.1 b	2.6 b	1.8 a	1.2 c	1.2 b
	Practice areas							
2006	2.9 a	2.1 a	2.3 a	2.4 a	5.2 a	3.6 a	2.6 a	2.3 a
2014	2.2 b	1.8 b	1.6 b	1.9 ab	3.4 b	2.9 ab	2.1 b	1.7 b
2021	1.8 c	1.2 c	1.6 b	1.7 b	3.2 b	2.2 b	1.6 c	1.3 b
	Natural areas							
2006	1.1 a	1.0 a	0.9 a	1.2 a	1.7 a	1.2 a	1.1 a	0.8 a
2014	1.1 a	0.9 a	0.7 a	1.1 a	1.5 a	1.6 a	0.9 a	1.2 a
2021	1.0 a	0.6 a	0.8 a	1.1 a	1.7 a	1.4 a	0.9 a	0.6 a
	Grounds							
2006	2.2 a	1.8 a	1.8 a	2.5 a	3.5 a	2.3 a	2.0 a	1.9 a
2014	1.6 b	1.3 b	1.3 b	2.2 ab	2.5 b	2.5 a	1.5 b	1.6 ab
2021	1.5 c	0.9 c	1.2 b	1.7 b	2.6 b	2.3 a	1.5 b	1.3 b

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.
[ii] 1 lb/1000 ft^2 = 48.8243 kg·ha^{-1}.
[iii] Within columns, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.

results provide sufficient evidence to warrant concern and justify further research to determine if soil testing actually results in greater N applications, or if the association is coincidental.

The three most important factors used when making nutrient application decisions in 2021 were visual observation, weather, and previous product performance (Table 11). The importance of the top three factors declined from 2006 to 2021, but they have remained the most important each year. Turfgrass wear, fertilizer cost, regulatory requirement, and growth prediction models increased in importance from 2006 to 2021, whereas most of the remaining factors were rated less important in 2021 than in 2006. Turfgrass damage resulting from traffic reduces turfgrass quality associated with playability, and wear tolerance has been documented to increase as a result of applied N (Hoffman et al. 2010). Therefore, placing greater importance on turfgrass wear as a decision factor associated with nutrient applications is consistent with best management practices.

The most common management practices used with the intent of reducing reliance on applied nutrients were fertilizing based on soil test results, returning turfgrass clippings, and precision fertilizer applications (Fig. 5). Using plant growth models and stopping overseeding were the only two management practices that increased relative to 2014. The percentage of facilities using all other management practices in 2021 were either equivalent to or less than that of 2014. Soil analysis was the seventh most important out of 22 nutrient application decision factors; it was used by 43% of golf facilities with the intent of reducing reliance on fertilizers and by 85% of golf facilities on putting greens (Table 12). Therefore, soil testing is an important and common practice. However, basing fertilizer decisions on soil test results does not appear to be associated with nutrient conservation based on the finding that golf facilities that conducted soil tests applied more nutrients than golf facilities

Table 8. Median nitrogen (N), available phosphorus (P_2O_5), and soluble potash (K_2O) use per golf facility within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
Yr	Nutrients applied (tons/yr per facility)[ii]							
	N							
2006	5.8 a[iii]	4.8 a	3.4 a	5.8 a	10.0 a	12.8 a	5.1 a	6.2 a
2014	4.0 b	2.6 c	3.4 a	4.5 a	6.0 b	8.9 a	4.1 a	5.2 ab
2021	3.5 b	3.3 b	2.8 a	3.7 a	5.4 b	2.1 b	2.9 b	3.8 b
	P_2O_5							
2006	1.6 a	1.3 a	1.1 a	2.1 a	2.2 a	4.8 a	1.8 a	1.8 a
2014	0.5 b	0.2 b	0.4 b	0.9 ab	1.7 a	1.3 b	0.6 b	0.9 ab
2021	0.5 b	0.2 b	0.6 b	0.7 b	0.8 b	1.4 b	0.5 b	0.6 b
	K_2O							
2006	5.0 a	3.9 a	2.9 a	4.9 a	9.7 a	10.5 a	4.7 a	4.7 a
2014	2.9 b	1.5 b	2.3 ab	3.4 ab	6.2 b	4.1 ab	3.1 b	3.3 ab
2021	2.3 c	1.6 b	2.0 b	1.8 b	4.7 b	3.0 b	1.6 c	1.8 b

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.
[ii] 1 ton = 0.9072 Mg.
[iii] Within columns, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.

Table 9. Frequency of United States golf facilities that reported applications of nitrogen (N), available phosphorus (P_2O_5), and soluble potash (K_2O) to each golf facility feature in 2006, 2014, and 2021.

	Greens	Tees	Fairways	Roughs	Practice areas	Natural areas	Grounds
Yr	Golf facilities (%)						
	N						
2006	99.9 a[i]	98.1 a	96.2 a	73.2 a	59.6 a	8.0 a	56.5 a
2014	99.3 b	96.8 ab	91.7 b	65.2 b	59.6 a	3.9 b	58.0 a
2021	99.5 b	96.5 b	92.7 b	64.8 b	60.4 a	3.8 b	54.1 a
	P_2O_5						
2006	92.4 a	88.7 a	82.1 a	61.1 a	51.8 a	6.1 a	48.6 a
2014	80.5 b	65.2 b	51.4 b	32.2 b	35.7 b	1.7 b	30.1 b
2021	74.9 c	59.4 c	49.5 b	31.1 b	35.7 b	1.8 b	26.1 c
	K_2O						
2006	96.8 a	94.8 a	92.3 a	69.3 a	57.2 a	8.3 a	54.5 a
2014	95.0 ab	89.0 b	83.0 b	56.4 b	53.3 b	3.3 b	52.0 a
2021	92.8 b	86.3 b	80.1 b	54.9 b	53.4 a	3.2 b	46.0 b

[i] Within columns, values followed by a common letter are not significantly different according to chi-square test at the 10% significance level.

that did not (Fig. 4). These findings provide no evidence that soil testing is associated with nutrient conservation under golf course conditions. Soil testing is intended to provide an evidence-based method of managing nutrients, but most turfgrass soil testing research has been conducted using greenhouses or small-scale field studies (Guevara 2021; Kreuser et al. 2012; Liu et al. 2008). It is unknown why soil testing was associated with increased nutrient rates. It is possible, if not probable, that golf facilities that conducted soil tests were also associated with facilities operating with greater fertilizer budgets. It is also possible that the increased amount of nutrients applied by soil-testing golf facilities was necessary to meet turfgrass performance expectations. Further research is needed to explain the association between soil testing and applied nutrients. Regardless, scientists, educators, and professionals who promote the use of soil testing to enhance nutrient use efficiency may need to reconsider if and how this long-standing management practice can be effectively implemented under golf course conditions.

The reduced usage of soil tests for nutrient applications (Fig. 5) may be considered beneficial. Soil tests can be used to determine if some nutrients should be applied but cannot be used to determine a specific amount of nutrient unless the soil test recommendation is based upon a calibration conducted on the specific turfgrass and soil from which the sample was taken. Nationally, the percentage of golf facilities that conducted soil tests on each course feature declined from 2006 to 2021 (Table 12), which further supports the finding that fewer golf facilities are using soil testing to manage nutrient applications. In 2020, 13% of United States golf facilities used reclaimed water, which accounted for 21% of irrigation water used on golf courses (Shaddox et al. 2022). Reclaimed water generally contains N and P; however, in 2021,

Table 10. Frequency of soil extractant used for analysis of phosphorus and non-phosphorus nutrients on golf facilities within the United States and regions (Fig. 1) in 2021.

	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
Extractant	**Golf facilities (%)**							
	Phosphorus analysis							
Saturated paste	47	45	51	44	41	60	48	51
Mehlich-3	23	18	27	19	25	12	33	15
Bray	14	23	13	21	10	18	5	21
Mehlich-1	11	7	5	14	22	–	11	3
Olsen	3	5	1	2	1	10	2	11
Modified Morgan	1	2	4	–	1	–	1	–
	Nonphosphorus nutrient analysis							
Saturated paste	57	56	61	59	49	79	54	67
Mehlich-3	22	18	20	22	22	10	33	14
Mehlich-1	12	10	7	14	22	–	10	3
Bray	5	5	7	5	5	5	3	9
Olsen	2	6	2	–	0	4	–	7
Modified Morgan	2	4	4	–	1	2	1	–

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.

fewer golf course superintendents indicated they considered the nutrients in reclaimed water with the intent of reducing reliance on applied nutrients (i.e., fertilizer) (Fig. 5). Furthermore, golf course superintendents ranked the nutrient content of the effluent water source as the third least important factor (out of 22) when making nutrient application decisions (Table 11).

Management practices used with the intent of reducing reliance on applied nutrients were not associated with the reduction of applied N (Table 13). Fertilizing based on soil test results and changing turfgrass species and/or improved cultivars with the intent of reducing reliance on applied nutrients were associated with 60% and 48% increases in applied N, respectively. The increased amount of N applied to golf facilities that used soil testing to reduce their reliance on applied nutrients is consistent with the increased N rates applied to golf facilities that conducted soil tests (Fig. 4). As previously stated, it is not known whether the relationship between soil testing and applied nutrients results in the increase in applied nutrients, or whether the increase is the result of some other factor. A future covariant survey analysis may provide more specific and valuable results. Golf facilities that transition to different turfgrass cultivars normally experience an establishment period that often includes increased N applied for 8 to 12 weeks to shorten the establishment phase (Braun et al. 2021). Generally, increased N rates are subsequently reduced when the turfgrass is established. The amount of N applied during turfgrass establishment may partially explain the association between golf facilities that changed turfgrass cultivars and increased N applied.

Similar to N, fertilizing based on soil test results to reduce reliance on applied nutrients was associated with 72% and 82% increases in applied P_2O_5 and K_2O, respectively (Table 13). However, returning clippings, precision fertilizer applications, reducing turfgrass acres, and considering N release using N mineralization models from soil organic matter were associated with 42%, 28%, 29%, and 32% reductions in applied P_2O_5, respectively. Reducing turfgrass acres was also associated with a 23% reduction in K_2O applied, whereas no other management

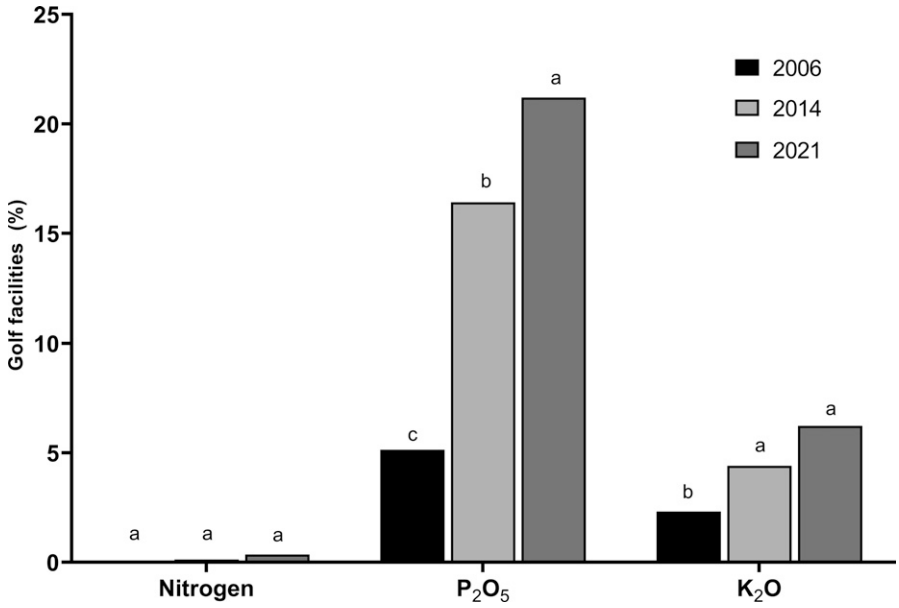

Fig. 3. Frequency of United States golf facilities that reported no applications of nitrogen (N), available phosphorus (P_2O_5), and soluble potash (K_2O) in 2006, 2014, and 2021. Bars with a common letter are not significantly different according to chi-square test at the 10% significance level.

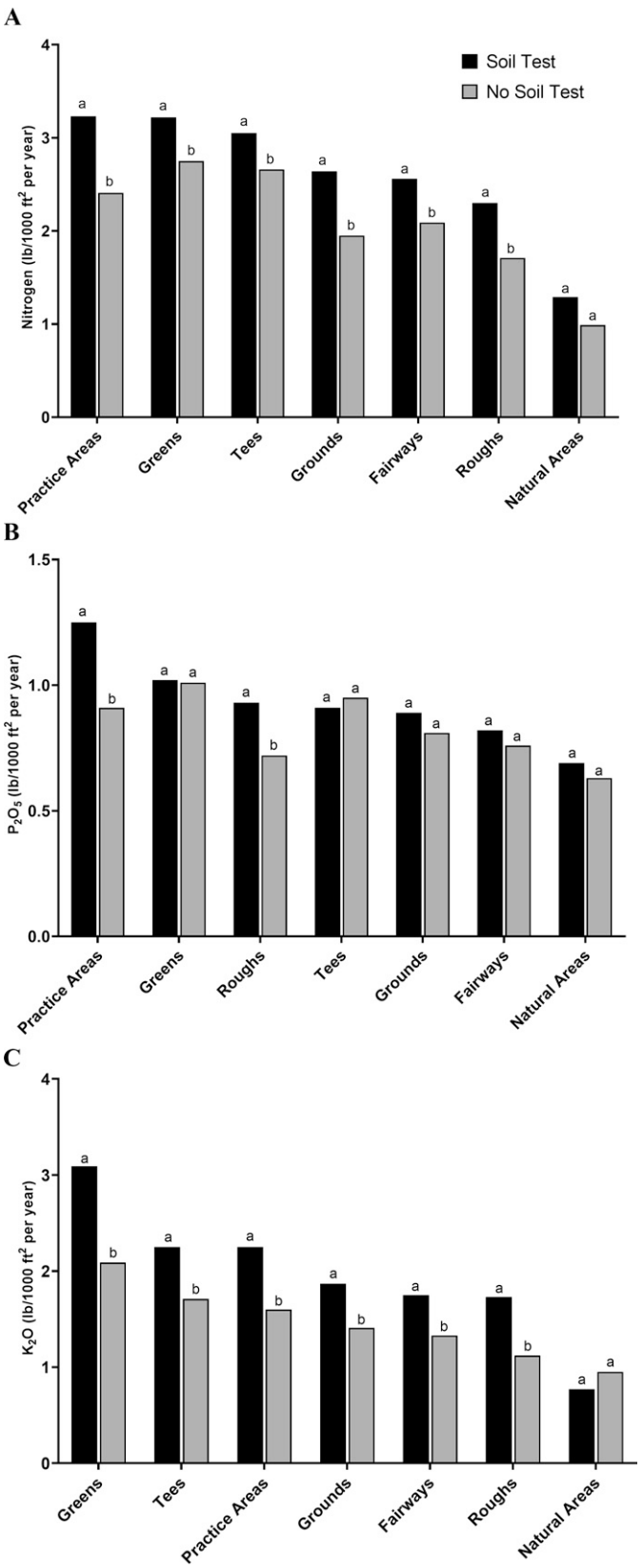

Fig. 4. Nutrients use rates of (A) nitrogen (N), (B) available phosphorus (P_2O_5), and (C) soluble potash (K_2O) on United States golf facilities that conducted soil tests or did not in 2021. Bars with a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level. 1 lb/1000 ft^2 = 48.8243 kg·ha^{-1}.

practice was associated with reduced K_2O applied. As previously discussed, these results do not provide evidence of causality. Because facilities that indicated they used soil testing to reduce their reliance on applied nutrients were associated with applying more nutrients, it is possible the soil test interpretation and/or nutrient recommendations should be investigated further to determine if the nutrients applied were based on accurate correlations and calibrations. It remains unknown whether the increased amount of P_2O_5 and K_2O was necessary to achieve a desired turfgrass quality. Previous research has shown that the likelihood of growing turfgrass on P- or K-deficient soils may be rare and varies depending on location (Shaddox and Munshaw 2020; Shaddox et al. 2019). Therefore, it is possible, albeit unlikely, that the increased amounts of applied P_2O_5 and K_2O were required. Future surveys that include a turfgrass quality component may help to determine if the increased amounts of N, P_2O_5, and K_2O were necessary.

The saturated paste extract was the most common extract used for P and non-P nutrient analyses both nationally and within each region (Table 10). Saturated paste extraction is an evidence-based procedure for determining salinity (Sonnevelt and van den Ende 1971) and acidity (Thomas 1996); however, it has not been correlated or calibrated with any nutrient other than boron (Keren et al. 1985), and it has not been correlated or calibrated with any nutrient applied to turfgrass. It remains unknown how many, if any, nutrients were applied to golf facilities as a result of using the saturated paste extraction. However, because the finding that approximately one-half of golf facilities used a nonevidence-based method for P analysis, scientists and educators should ensure that proper soil test selection is included in their education efforts. Educational efforts designed to guide superintendents toward the use of evidence-based methods for P analysis and application may aid in reducing this percentage, which, in turn, may likely reduce maintenance costs and environmental risk.

The ratios of N to P_2O_5 and K_2O to P_2O_5 varied from 1.4 to 3.4 and from 1.5 to 2.9, respectively, depending on the course feature (Table 14). Greens, tees, and fairways received the greatest ratio of N to P_2O_5, which is consistent with prioritizing N applications

Table 11. Importance of factors when making nutrient application decisions on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

	2006	2014	2021
Decision factor	Importance (scale, 1–5)[i]		
Visual observation/scouting	4.10 a[ii]	4.09 a	4.00 b
Precipitation/temperature/weather	4.12 a	4.14 a	3.99 b
Previous product performance on your established turf	4.08 a	4.09 a	3.98 b
Disease problems/pressure	4.06 a	3.98 b	3.90 c
Traffic/wear	3.77 b	3.88 a	3.89 a
Turf species	3.99 a	3.88 b	3.86 b
Soils/soil analysis	4.11 a	4.02 b	3.85 c
Golfers' expectations for turf performance	3.79 a	3.80 a	3.74 a
Cost of fertilizer	3.57 c	3.79 a	3.66 b
Length of growing season	3.77 a	3.74 a	3.63 b
Reduction of environmental impact	[iii]	3.61 a	3.44 b
Clipping production	3.35 a	3.39 a	3.40 a
Golf events calendar	3.50 a	3.54 a	3.33 b
Regulatory requirements	2.65 c	3.04 a	2.90 b
Turf growth prediction models	2.75 b	2.83 ab	2.89 a
Manufacturer recommendations	2.80 ab	2.86 a	2.77 b
University recommendations	2.71 b	2.87 a	2.67 b
Consultant/service provider recommendations	2.62 a	2.54 ab	2.47 b
Tissue analysis	2.49 a	2.42 ab	2.35 b
Nutrient content of effluent water source	1.97 ab	1.89 b	2.01 a
Adjacent property owner's maintenance standards	1.77 c	1.96 a	1.85 b
Overseeding warm season grasses with cool-season grasses	–	1.31 a	1.29 a

[i] Respondents rated factors using a scale of 1 to 5 scale, where 1 = not important at all and 5 = extremely important.
[ii] Within rows, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.
[iii] Not asked in 2006.

for the more visible and playable course features. Greens, tees, and fairways receive greater traffic than other areas of the course; as a result, they often require greater quantities of N relative to P_2O_5 to aid in recuperation from damage (Hoffman et al., 2010). Golf course superintendents reported that less K_2O was applied relative to P_2O_5 overall and on greens, tees, fairways, and practice areas. Potassium applications rarely result in a direct beneficial turfgrass response (Frank and Guertal 2013) and, in fact, have been documented to result in increased disease incidence under some conditions (Bier et al. 2018). Therefore, reducing the ratio of K_2O to P_2O_5 will likely have no negative impact on turfgrass quality as long as soil potassium levels are adequate (Sartain 2002).

Written nutrient management plans can help guide nutrient applications and result in increased nutrient use efficiency. Nationally, 43% of golf facilities reported having a written nutrient management plan, with the percentage varying across regions from 35% in the Northeast to 52% in the North Central, respectively (data not shown). The percentage of golf facilities using written nutrient management plans remained equivalent to those in 2006 nationally and within each region. Although the percentage of facilities using a written nutrient management plan did not change from 2006 to 2021, recent educational efforts have resulted in the development of state- and facility-specific best management practices, which may include written nutrient management plans (Golf Course Superintendents Association of America 2021a).

The percentage of facilities using natural organic N sources declined nationally and within the North Central, Northeast, Southwest, and Transition regions (Table 15). Natural organic N sources are often viewed as being more beneficial for turfgrass and the environment than synthetic N sources. Compared with soluble synthetic fertilizers, natural organics contain relatively low salts, thereby resulting in a lower burn potential (Carrow et al. 2001). Furthermore, natural organic fertilizers have been documented to result in reduced nutrient leaching compared with synthetic fertilizers under some conditions (Guillard and Kopp 2004). However, the notion that natural organics are more beneficial than synthetic fertilizers may not be entirely accurate. When natural organic fertilizers are applied based on the amount of N required by the plant, greater than necessary amounts of P_2O_5 are likely to be applied and may result in greater P in runoff than synthetic fertilizers (Easton and Petrovic 2004). This is because of natural organic fertilizers containing a low ratio of N to P_2O_5, which may be as low as 1:1 and cannot be avoided because of both the N and P_2O_5 being contained within the same fertilizer granule. Any amount of P_2O_5 applied without an evidence-based justification increases the risk of environmental impairment and should be avoided. Moreover, natural organic fertilizers may be as much as seven-fold more expensive than urea (Shaddox and Unruh 2021). Therefore, the reduction in the use of natural organic sources may be beneficial both environmentally and fiscally. Practitioners

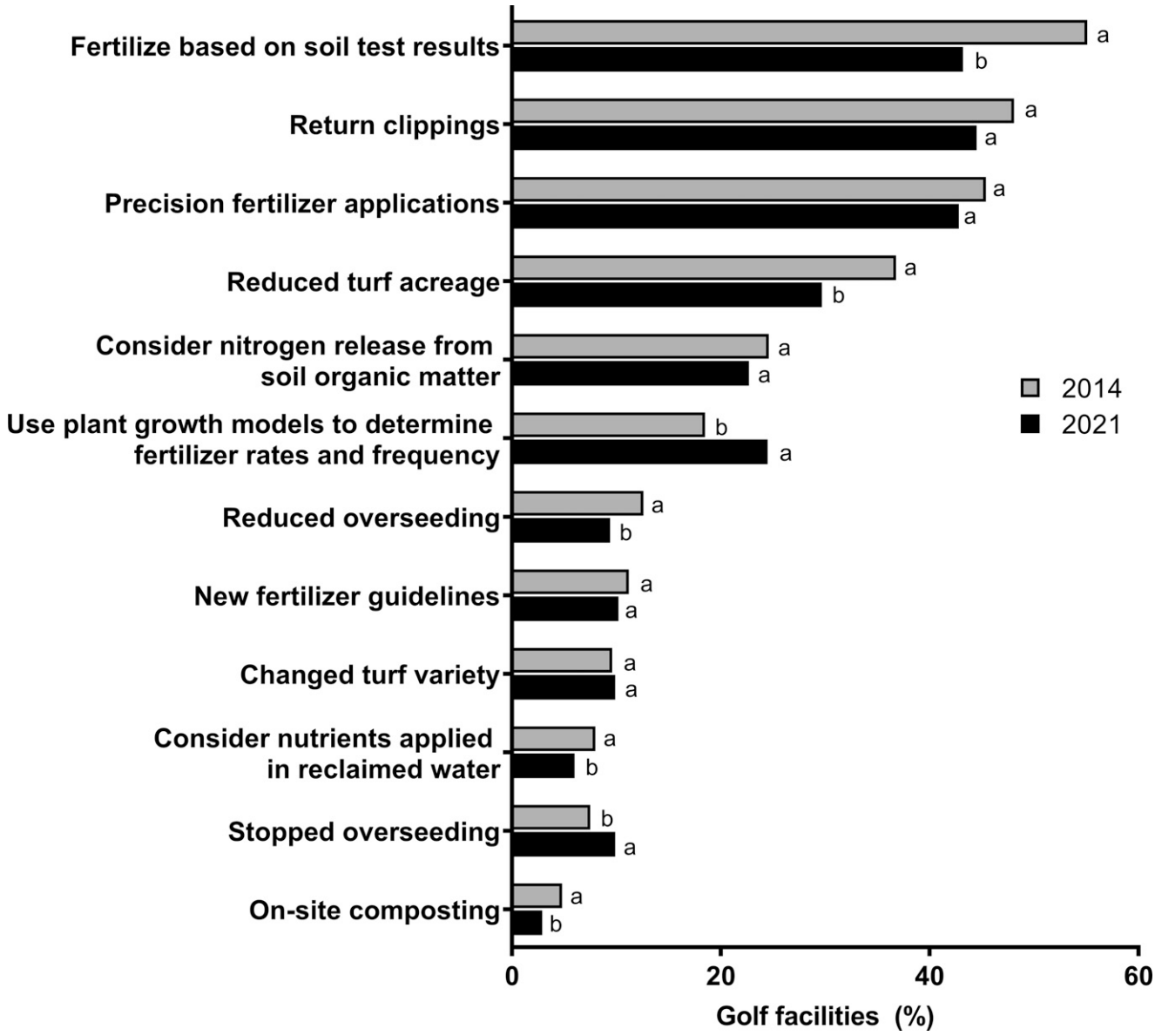

Fig. 5. Frequency of management practices used on United States golf facilities with the intent of reducing reliance on applied nutrients in 2014 and 2021. Bars with a common letter are not significantly different according to chi-square test at the 10% significance level.

should evaluate their nutrient sources and costs to enhance environmental stewardship and efficiency.

For the first time since 2006, the use of slow-release N declined nationally (Table 16). Concomitantly, the use of quick-release N increased nationally and within the North Central, Northeast, and Southeast regions. It is unknown what factors led to these changes. However, in Nov 2021, the cost of urea increased by more than 3.5-fold compared with the cost in Nov 2020, reaching a historic high of $900 per metric ton (Index Mundi 2022). Because most synthetic slow-release N sources used for turfgrass management are derived from urea, the cost of slow-release N sources increased accordingly. Shaddox and Unruh (2021) reported quick-release N sources cost less than slow-release N sources to maintain acceptable bermudagrass (*Cynodon dactylon*), even when applied using a method designed for slow-release N source performance. Therefore, the reduced use of slow-release N sources in 2021 compared with 2006 may be a primarily financial decision and may likely lead to cost-savings while potentially maintaining a desired level of turfgrass quality.

The percentage of golf facilities using soil amendments increased with each soil amendment except limestone (Table 17). The most common soil amendments used were humic substances, amino acids, and biostimulants, with 50% or more of golf facilities using at least one of the three. It is presumed by many that biostimulants enhance turfgrass beyond the response attributed to their nutrients. In fact, biostimulants have been documented to increase drought tolerance (Zhang and Ervin 2004). However, under low-stress conditions, biostimulants may result in little to no turfgrass

Table 12. Frequency of golf facilities within the United States and regions (Fig. 1) that soil-tested course features in 2006, 2014, and 2021.

	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
Yr	Golf facilities (%)							
	Greens							
2006	92 a[ii]	86 a	95 a	94 a	96 a	91 a	95 a	92 a
2014	91 a	85 a	91 b	92 a	98 a	93 a	88 b	91 a
2021	85 b	74 b	87 b	97 a	98 a	87 a	79 b	85 a
	Tees							
2006	70 a	62 a	77 a	74 a	80 a	64 a	69 a	62 a
2014	63 b	56 a	73 a	58 a	71 b	63 a	63 ab	53 a
2021	57 c	45 b	58 b	66 a	77 ab	60 a	53 b	50 a
	Fairways							
2006	75 a	66 a	78 a	77 a	83 a	83 a	71 a	75 a
2014	67 b	58 b	69 b	70 a	74 a	70 a	66 ab	68 a
2021	61 c	48 c	61 b	69 a	79 a	67 a	56 b	62 a
	Practice areas							
2006	31 a	18 a	27 a	26 a	51 a	31 a	32 a	32 a
2014	27 b	17 a	27 ab	15 a	41 b	31 a	29 ab	20 b
2021	23 c	10 b	21 b	19 a	38 b	28 a	26 b	17 b
	Roughs							
2006	22 a	10 a	21 a	16 a	34 a	31 a	27 a	21 a
2014	19 b	10 a	18 a	13 a	25 b	25 ab	23 a	21 a
2021	14 c	3 b	15 a	5 b	23 b	14 b	23 a	9 b
	Grounds							
2006	13 a	8 a	13 a	8 a	19 a	11 a	16 a	12 a
2014	12 a	8 a	13 a	6 ab	19 a	7 a	14 a	6 a
2021	7 b	2 b	9 a	3 b	11 b	5 a	11 a	6 a
	Natural areas							
2006	4 a	2 a	3 a	2 a	5 a	4 a	5 a	5 a
2014	3 a	1 a	4 a	2 a	2 b	4 a	3 ab	1 b
2021	1 b	<1 a	3 a	2 a	1 c	1 a	2 b	2 ab

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West–Mountain.
[ii] Within columns, values followed by a common letter are not significantly different according to chi-square test at the 10% significance level.

benefit (Bolton et al. 2022). Therefore, the benefit, if any, of biostiumulants applied to well-watered turfgrass is moot; therefore, the increased use of biostimulants is questionable. From 2014 to 2021, the percentage of facilities using gypsum declined to 44%. The use of gypsum is an evidence-based approach to remediate

Table 13. Association between management practice used with the intent of reducing reliance on applied nutrients and median nitrogen (N), available phosphorus (P_2O_5), and soluble potash (K_2O) applied on United States golf facilities in 2021.

	Was management practice used?					
	Yes	No	Yes	No	Yes	No
Management practice	N (tons/yr)[i]		P_2O_5 (tons/yr)		K_2O (tons/yr)	
Fertilize based on soil test results	4.40 a[ii]	2.75 b	0.63 a	0.36 b	3.08 a	1.69 b
Return clippings	3.44 a	3.55 a	0.37 b	0.64 a	2.16 a	2.48 a
Use precision fertilizer applications	3.75 a	3.26 a	0.40 b	0.56 a	2.38 a	2.22 a
Reduce turf acreage	3.27 a	3.62 a	0.38 b	0.54 a	1.93 b	2.52 a
Consider nitrogen release from soil organic matter	3.55 a	3.47 a	0.36 b	0.53 a	2.11 a	2.36 a
Use plant growth models to determine fertilizer rates and frequency	3.96 a	3.32 a	0.57 a	0.44 a	2.34 a	2.28 a
Reduce overseeding	3.88 a	3.45 a	0.71 a	0.45 a	2.95 a	2.22 a
Use new fertilizer guidelines	4.40 a	3.40 a	0.60 a	0.46 a	2.57 a	2.27 a
Change turf cultivar	5.00 a	3.37 b	0.41 a	0.48 a	3.57 a	2.19 b
Consider nutrients applied in reclaimed water	3.19 a	3.51 a	0.35 a	0.49 a	2.27 a	2.30 a
Stop overseeding	4.31 a	3.38 a	1.21 a	0.42 b	3.56 a	2.14 b
Compost on-site	3.61 a	3.48 a	0.33 a	0.48 a	1.48 a	2.34 a

[i] 1 ton = 0.9072 Mg.
[ii] Within rows and nutrient, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.

Table 14. Ratios of applied nitrogen (N), available phosphorus (P_2O_5), and soluble potash (K_2O) on United States golf facilities in 2006, 2014, and 2021.

Yr	N	P_2O_5	K_2O
		Total	
2006	2.6 b[i]	1	2.2 c
2014	5.7 a	1	3.9 a
2021	4.8 a	1	3.1 b
		Greens	
2006	3.0 c	1	3.0 b
2014	3.6 a	1	3.4 a
2021	3.3 b	1	2.9 b
		Tees	
2006	3.0 b	1	2.5 a
2014	3.4 a	1	2.5 a
2021	3.4 a	1	2.3 b
		Fairways	
2006	3.1 b	1	2.5 a
2014	3.3 a	1	2.5 a
2021	3.3 a	1	2.3 b
		Roughs	
2006	2.8 a	1	2.3 a
2014	2.9 a	1	2.3 a
2021	3.0 a	1	2.2 a
		Practice	
2006	2.9 b	1	2.4 a
2014	3.3 a	1	2.4 a
2021	3.0 ab	1	2.1 b
		Natural areas	
2006	2.0 a	1	1.6 a
2014	1.7 a	1	1.9 a
2021	1.4 a	1	1.5 a
		Grounds	
2006	2.8 b	1	2.2 a
2014	3.1 a	1	2.3 a
2021	2.9 ab	1	2.1 a

[i] Within columns, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.

sodic soils and supply sulfate to sulfate-deficient soils (Carrow and Duncan 2012). However, sodic soils in the continental United States are primarily encountered in the Southwest arid regions and rarely encountered elsewhere (Wicke et al. 2011). Sulfur-deficient soils are also rarely encountered (Feinberg et al. 2021) despite sulfur-deficient soils becoming more frequent because of reductions in sulfur dioxide emissions during the past two decades (Chang et al. 2022). Therefore, the high frequency of gypsum use appears to be agronomically unjustified. Determining why gypsum is so prevalently used on United States golf facilities would be valuable information toward building educational programs designed to inform turfgrass managers when and why gypsum should be used.

The number of nutrient applications per year has increased from 2006 to 2021 for each course feature except roughs (Table 18). The ability of superintendents to have greater control over their turfgrass nutrition program likely explains much of this increase. The previously noted reduction in slow-release N and concomitant increase in quick-release N supports this postulate. When soluble N sources, such as urea, are sprayed rather than spread on the turfgrass, more frequent applications are often required because of the reduced application rate. The increased usage of some amendments that are commonly available in a liquid form, such as amino acids, may also have a role in the increase in nutrient applications. Liquid applications may allow for a more precise application compared with granular fertilizers but require lower rates to minimize the risk of phytotoxicity. As a result, liquid fertilizers are commonly applied frequently, but at low rates, which may explain the increase in nutrient applications.

Conclusions

From 2006 to 2021, projected tons of N, P_2O_5, and K_2O applied to United States golf facilities have declined by 41%, 59%, and 54%, respectively. The decline was likely a result of golf facility closures, reduced fertilized acres, and nutrient rate reductions. Nutrient restrictions likely influenced the amount of P_2O_5 applied. The percentage of golf facilities that did not apply P_2O_5 or K_2O increased from 2006 to 2021. Although the percentage of golf facilities that conducted soil tests declined from 2006 to 2021, the application of soil tests continues to be a potential concern because more nutrients were applied on golf facilities that conducted soil tests compared with those that did not. Although soil testing may be positioned as a conservation practice, the finding that soil testing was associated with increased N, P_2O_5, and K_2O application rates suggests otherwise; therefore, additional emphasis on the tenets of proper soil testing (i.e., sampling, testing, interpretation, and recommendation) should be provided. Nearly half of United States golf facilities used the saturated pasted soil extractant for soil P analysis, which is not condoned by turfgrass soil scientists. The most important factors used when making nutrient application decisions remained consistent with those of prior years (visual observations, weather, and previous product performance). Golf course superintendents appear to place importance on nutrient management as evidenced by the reduction in fertilized acres on operational facilities and the reduction of nutrient application rates.

Table 15. Frequency of natural organic nitrogen use on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
Yr				Golf facilities (%)				
2006	64 a[ii]	56 a	75 a	66 a	67 a	56 a	65 a	57 a
2014	61 a	51 ab	74 a	61 a	64 a	67 a	64 ab	53 a
2021	54 b	47 b	56 b	56 a	62 a	36 b	55 b	62 a

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.
[ii] Within columns, values followed by a common letter are not significantly different according to chi-square test at the 10% significance level.

Table 16. Percentage of slow- and quick-release nitrogen (N) applied on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

Yr	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
	Slow-release N (%)							
2006	66 a[ii]	70 a	69 a	60 a	65 a	57 a	62 a	65 a
2014	65 a	69 ab	71 a	59 a	62 ab	49 b	61 a	68 a
2021	62 b	66 b	63 b	54 a	60 b	48 b	61 a	68 a
	Quick-release N (%)							
2006	31 b	28 b	29 b	35 a	31 b	42 b	34 a	33 a
2014	32 b	29 b	28 b	38 a	33 ab	49 a	36 a	29 a
2021	35 a	32 a	35 a	42 a	36 a	49 ab	35 a	30 a

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.
[ii] Within columns, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.

Table 17. Frequency of soil amendment and supplement use on United States golf courses in 2006, 2014, and 2021.

Soil amendment	2006	2014	2021
	Golf facilities (%)		
Used at least one amendment	76 b[i]	83 a	84 a
Humic materials	41 c	53 b	58 a
Amino acids/proteins	38 b	49 a	52 a
Biostimulants	43 b	48 a	50 a
Gypsum	34 c	49 a	44 b
Sulfur	8 b	27 a	25 a
Limestone	22 b	26 a	22 b
Sugars (sucrose, molasses, etc.)	14 b	18 a	18 a
Microbial inoculants	14 b	20 a	18 a
Compost	13 b	14 ab	16 a
Biocontrol agents	6 b	8 a	10 a
Calcium chloride	5 b	9 a	8 a
Compost teas	3 c	8 a	6 b

[i] Within rows, values followed by a common letter are not significantly different according to chi-square test at the 10% significance level.

Table 18. Number of nutrient applications performed annually on golf facilities within the United States and regions (Fig. 1) in 2006, 2014, and 2021.

Yr	US	NC[i]	NE	Pac	SE	SW	Trans	UWM
	Nutrient applications (no./year)							
	Greens							
2006	11.9 c[ii]	8.9 b	9.3 c	16.1 b	20.0 b	17.2 b	12.1 b	9.5 b
2014	14.4 b	9.7 b	10.6 b	20.7 a	30.3 a	22.2 a	14.2 a	13.7 a
2021	16.3 a	11.0 a	13.7 a	22.2 a	31.8 a	23.5 a	15.7 a	16.3 a
	Tees							
2006	5.4 b	5.2 b	5.7 b	6.7 a	6.5 b	5.9 b	4.7 a	3.8 b
2014	5.5 b	5.1 b	5.4 b	7.2 a	7.7 a	8.8 a	4.3 a	4.3 ab
2021	6.2 a	5.8 a	7.1 a	7.5 a	7.7 a	7.7 a	4.6 a	4.6 a
	Fairways							
2006	3.5 c	3.2 b	3.1 b	4.0 a	4.4 b	5.0 b	3.4 b	2.6 b
2014	4.0 b	3.5 ab	3.5 b	5.3 a	5.7 a	6.3 ab	3.9 a	3.0 b
2021	4.6 a	3.9 a	4.6 a	4.5 a	6.5 a	7.9 a	3.6 ab	4.1 a
	Roughs							
2006	2.6 a	1.8 a	2.0 a	3.0 a	3.9 a	4.4 a	2.4 a	2.1 a
2014	2.5 a	1.9 a	2.1 a	2.4 a	3.7 a	4.8 a	2.3 a	2.1 a
2021	2.6 a	2.0 a	2.1 a	2.8 a	3.9 a	4.4 a	2.2 a	2.5 a

[i] NC = North Central; NE = Northeast; Pac = Pacific; SE = Southeast; SW = Southwest; Trans = Transition; US = United States; UWM = Upper West/Mountain.
[ii] Within columns, values followed by a common letter are not significantly different according to the Tukey-Kramer test at the 10% significance level.

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Supplemental Table S1. 2021 nutrient survey responses and weighting factors categorized by region (Fig. 1), facility type, number of holes, and green fee.

Region	Facility type	Holes (no.)	Green fee ($)	Golf facilities		Survey responses		Wt
				(no.)	(%)	(no.)	(%)	
Northeast	All	9	All	647	4.6	28	1.9	2.378
Northeast	Public	18	< 55	508	3.6	26	1.8	2.011
Northeast	Public	18	≥ 55	557	4.0	65	4.5	0.882
Northeast	Private	18	All	579	4.1	99	6.9	0.602
Northeast	All	27+	All	179	1.3	27	1.9	0.682
North Central	All	9	All	1144	8.2	22	1.5	5.351
North Central	Public	18	< 55	1183	8.4	64	4.4	1.902
North Central	Public	18	≥ 55	472	3.4	73	5.1	0.665
North Central	Private	18	All	451	3.2	83	5.7	0.559
North Central	All	27+	All	305	2.2	33	2.3	0.951
Transition	All	9	All	640	4.6	17	1.2	3.874
Transition	Public	18	< 55	818	5.8	61	4.2	1.380
Transition	Public	18	≥ 55	355	2.5	52	3.6	0.702
Transition	Private	18	All	520	3.7	90	6.2	0.595
Transition	All	27+	All	176	1.3	27	1.9	0.671
Southeast	All	9	All	458	3.3	6	0.4	7.855
Southeast	Public	18	< 55	744	5.3	59	4.1	1.298
Southeast	Public	18	≥ 55	503	3.6	66	4.6	0.784
Southeast	Private	18	All	684	4.9	136	9.4	0.518
Southeast	All	27+	All	348	2.5	62	4.3	0.578
Southwest	All	9	All	241	1.7	4	0.3	6.200
Southwest	Public	18	< 55	169	1.2	13	0.9	1.338
Southwest	Public	18	≥ 55	335	2.4	44	3.0	0.783
Southwest	Private	18	All	225	1.6	40	2.8	0.579
Southwest	All	27+	All	168	1.2	15	1.0	1.152
Upper West/Mountain	All	9	All	384	2.7	12	0.8	3.293
Upper West/Mountain	Public	18	< 55	179	1.3	27	1.9	0.682
Upper West/Mountain	Public	18	≥ 55	272	1.9	59	4.1	0.474
Upper West/Mountain	Private	18	All	149	1.1	35	2.4	0.438
Upper West/Mountain	All	27+	All	75	0.5	13	0.9	0.594
Pacific	All	9	All	162	1.2	6	0.4	2.778
Pacific	Public	18	< 55	52	0.4	3	0.2	1.784
Pacific	Public	18	≥ 55	184	1.3	42	2.9	0.451
Pacific	Private	18	All	112	0.8	26	1.8	0.443
Pacific	All	27+	All	55	0.4	9	0.6	0.629