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Energy use and greenhouse gas emissions from turf management of two Swedish golf courses

Pernilla Tidåker[a,*], Therese Wesström[b], Thomas Kätterer[c]

[a] Swedish Institute of Agricultural and Environmental Engineering, Box 7033, 750 07 Uppsala, Sweden
[b] South Pole Group, Waterfront Building, Klarabergsviadukten 63, 101 23 Stockholm, Sweden
[c] Swedish University of Agricultural Sciences, Department of Ecology, Box 7044, 750 07 Uppsala, Sweden

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ABSTRACT

Turf management on golf courses entails frequent maintenance activities, such as mowing, irrigation and fertilisation, and relies on purchased inputs for optimal performance and aesthetic quality. Using life cycle assessment (LCA) methodology, this study evaluated energy use and greenhouse gas (GHG) emissions from management of two Swedish golf courses, divided into green, tee, fairway and rough, and identified options for improved management. Energy use and GHG emissions per unit area were highest for greens, followed by tees, fairways and roughs. However, when considering the entire golf course, both energy use and GHG emissions were mainly related to fairway and rough maintenance due to their larger area. Emissions of GHG for the two golf courses were 1.0 and 1.6 Mg CO_2e ha^{-1} year^{-1} as an area-weighted average, while the energy use was 14 and 19 GJ ha^{-1} year^{-1}. Mowing was the most energy-consuming activity, contributing 21 and 27% of the primary energy use for the two golf courses. In addition, irrigation and manufacturing of mineral fertiliser and machinery resulted in considerable energy use. Mowing and emissions associated with fertilisation (manufacturing of N fertiliser and soil emissions of N_2O occurring after application) contributed most to GHG emissions. Including the estimated mean annual soil C sequestration rate for fairway and rough in the assessment considerably reduced the carbon footprint for fairway and turned the rough into a sink for GHG. Emissions of N_2O from decomposition of grass clippings may be a potential hotspot for GHG emissions, but the high spatial and temporal variability of values reported in the literature makes it difficult to estimate these emissions for specific management regimes. Lowering the application rate of N mineral fertiliser, particularly on fairways, should be a high priority for golf courses trying to reduce their carbon footprint. However, measures must be adapted to the prevailing conditions at the specific golf course and the requirements set by golfers.

1. Introduction

Mitigation of climate change and reducing the current dependency on fossil fuels are interlinked challenges shaping policies in many sectors. The European Union (EU) has committed itself to reducing greenhouse gas (GHG) emissions, increasing the share of renewable energy supply and improving energy efficiency, all by 20% by 2020 (European Commission, 2007), and this commitment requires immediate measures in all sectors of society.

There are more than 500 golf courses, occupying approximately 28,000 ha, in Sweden (Statistics Sweden, 2013). Golf is associated with several benefits, e.g. it provides recreational value for the many people who play the game, enhances local biodiversity through extensively managed roughs in areas with intensively managed agriculture (Tanner and Gange, 2005) and promotes soil carbon (C) sequestration (Qian and Follett, 2002; Selhorst and Lal, 2011). Managed turfgrass systems achieve significantly higher C sequestration than arable land and extensively managed grassland (Qian and Follett, 2012). However, turfgrass maintenance on golf courses is reliant on repeated mowing, which requires fossil energy and releases GHG emissions to the atmosphere, mainly as carbon dioxide (CO_2). High turfgrass quality also requires other maintenance practices such as irrigation, fertilisation, vertical cutting, aeration and sand dressing, all with associated environmental impacts. Furthermore, nitrogen (N) from fertilisers and plant residues enhances nitrification and denitrification, which may increase emissions of nitrous oxide (N_2O). Intensive turfgrass management combining frequent irrigation and fertilisation can

* Corresponding author.
E-mail address: pernilla.tidaker@jti.se (P. Tidåker).

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enhance N_2O losses, particularly if water is applied immediately after fertilisation (Gu et al., 2015). However, soil N_2O production is associated with high variability depending on soil properties and management, which poses a great challenge when estimating N_2O emissions (Li et al., 2013). Emissions of N_2O are particularly worrisome since N_2O is a potent greenhouse gas with high global warming potential (GWP). The GWP of a certain gas is a measure of how much heat is trapped in the atmosphere relative to the amount of heat trapped by CO_2 over a specific time interval (IPCC, 2007). The concept of GWP for different GHG makes it possible to add them together to obtain total GWP for an entire system.

Energy use and GHG emissions are not only associated with the maintenance activities performed on the golf courses, since there are also indirect environmental burdens related to production of purchased inputs such as mineral fertilisers, fuel, machinery and transport of sand used for dressing. Life cycle assessment (LCA) is a comprehensive methodology addressing both direct and indirect energy use and emissions along the entire value chain in order to identify environmental hotspots. LCA is a commonly used standardised procedure for identifying opportunities for improved environmental performance and providing decision support for stakeholders in strategic planning and development (ISO, 2006). Carbon footprinting, a subset of a full LCA including only GHG emissions caused by a product or a service during its life cycle and summarised as CO_2-equivalents, is attracting increasing interest in the context of global warming mitigation (Röös, 2013).

A number of studies have evaluated GHG emissions from public and private lawns (e.g. Townsend-Small and Czimczik, 2010; Zirkle et al., 2011; Selhorst and Lal, 2013; Kong et al., 2014; Gu et al., 2015), while fewer studies are available for golf courses. Bartlett and James (2011) modelled GHG emissions from two golf courses in the UK and determined the balance between soil C sequestration and emissions from turf management. They assumed the same sequestration rate for the treeless components of the golf courses (green, tee, fairway and rough), independent of time since construction, mowing frequency and fertilisation rate, and found that the main contribution to GHG emissions came from mowing and production of fertilisers. Selhorst and Lal (2011) included C release due to different maintenance practices, summarised for the entire golf course, but excluded GHG emissions other than CO_2.

Depending on the prevailing climatic and edaphic conditions, turf management differs between locations. In addition, the different playable areas on a golf course are managed with differing intensity. In order to devise and implement efficient and well-adjusted measures for sustainable turf management, more knowledge is required about current energy use and GHG emissions from different components of the golf course and how these are distributed among different management activities.

The objective of the present study was thus to evaluate energy use and GHG emissions from annual management of two Swedish golf courses divided into green, tee, fairway and rough, and identify options for improved management. Particular emphasis was placed on maintenance operations and purchased inputs.

2. Material and methods

LCA methodology was used for evaluation of primary energy use and GHG emissions associated with turf management on golf courses during one year. Emissions of GHG were summarised as CO_2-equivalents (CO_2e) according to IPCC (2007), with a time horizon of 100 years. The results were presented both per hectare and for the entire courses.

Information on management practices was obtained through interviews with course managers of the golf courses. A brief description of different activities performed on the two golf courses is presented below, while a more detailed description can be found in Wesström (2015).

Table 1
Area of the different playable components included in the study, based on information provided by the golf course managers.

Course	Green (ha)	Tee (ha)	Fairway (ha)	Mowed rough (ha)	Total (ha)
Sigtuna	1.5	1.0	10	40	52.5
Uppsala	2.5	1.5	22	50	76

2.1. Description of the golf courses and their management

The golf courses included in the study are parkland courses situated in eastern Sweden. One of the golf clubs is located in the county of Uppsala and was established at its present site in 1964. It currently consists of one 18-hole course and two 9-hole courses, with a total playable area of 76 ha (Table 1). The other golf club is located outside the town Sigtuna, in between Stockholm and Uppsala. It has one 18-hole course constructed in the end of the 1960s, one 6-hole course and four practice greens. The golf courses are surrounded by a mosaic landscape characterised by agricultural land and forest. The total playable areas of the courses in Sigtuna and Uppsala were 52.5 and 76 ha, respectively (Table 1).

The golf season is approximately 26 weeks in Uppsala and 28 weeks in Sigtuna. Maintenance strategies differ considerably between the playing areas, in order to provide optimal performance and aesthetic quality for each specific area.

2.2. Application of fertiliser, pesticides, sand and water

The application rate of mineral fertilisers varies slightly between years. Sigtuna follows a specific fertiliser regime where the weekly fertilisation of greens and tees is pre-ordained. Here, we used data from 2013, which was considered to be a representative year. At Uppsala, fertiliser application is determined by the course manager and the data used in this study were representative of recent years. Fertilisers are applied manually to greens and tees on a regular basis throughout the season. Fairways are fertilised mechanically several times a year, while roughs do not receive any mineral fertiliser.

Fungicides and herbicides are occasionally used at both courses, while insecticides are not used at all. The rough in Uppsala receives herbicides once every other year.

The irrigation frequency is determined by precipitation. In general, greens, tees and fairways are irrigated approximately three times per week, while roughs are not irrigated at all. The irrigation water used in Sigtuna is pumped from a nearby lake and distributed via an underground pipe system, complemented with a hose when necessary. In Uppsala, the water is pumped from a nearby pond that also receives drainage water from the course. The amounts of water applied to the different parts of the course in this study were based on estimates by the managers, since no measured data were available. Sand for dressing is applied on greens and tees at both sites, and on fairways in Uppsala. This sand is transported 160 km to Uppsala and 50 km to Sigtuna. The amounts of mineral fertiliser, sand and pesticides applied and the volume of water used for irrigation are presented in Table 2.

2.3. Mowing and other maintenance practices

Greens are mowed seven times a week at Uppsala and five to six times a week at Sigtuna during the season. Tees and fairways are mowed three times a week at both sites during the season. Roughs are mowed once a week during the season, using a rotary mower. On all areas, seasonal mowing is complemented with some additional off-season mowing. The grass clippings from greens and tees

Table 2
Annual amounts of mineral fertilisers (N, P and K), sand, pesticides (active substance) and irrigation water applied per hectare to different parts of the golf courses in Sigtuna and Uppsala.

	Site	N (kg)	P (kg)	K (kg)	Pesticide (kg)	Sand (Mg)	Irrigation (10^3 m^3)
Green	Sigtuna	214	37	139	1.35	187	3.6
	Uppsala	190	80	190	1.35	120	3.0
Tee	Sigtuna	176	27	108		40	3.6
	Uppsala	220	40	220	1.35	33	3.0
Fairway	Sigtuna	89	12	40	0.39		1.8
	Uppsala	160	40	160	0.64	30	1.4

are collected by the mower at both sites and are either composted or spread out on other grass-covered areas. Clippings from fairways and roughs are not collected, but left on-site.

Aeration is performed with different frequency and machinery on different parts of the golf course. Deep-tine aeration and hole pipe aeration are mainly used on greens and tees. Verticutting is performed on greens at both sites, but only on tees at Sigtuna. Topdressing is most frequently used on greens. The seasonal management practices performed are summarised in Table 3.

In Sigtuna, 150 L of engine oil and 160 L of hydraulic oil are used annually for maintenance of the machinery, while the corresponding values in Uppsala are 60 and 150 L, respectively.

Mean fuel consumption for different operations is summarised in Table 4. All machinery was assumed to use diesel except for a pedestrian mower for greens and a walk-behind aerator for aeration of greens and tees, which consumed petrol. Data on mowing of greens and fairways in Uppsala were obtained from a previous study of fuel consumption per cycle of maintenance on the main golf course (Caple, 2008), while the course manager provided estimates for mowing in Sigtuna. No measurements were available for mowing the rough in Uppsala and therefore the estimated fuel consumption per occasion (6 L ha^{-1}) at Sigtuna was also used for Uppsala. Fuel consumption for aeration was based on assumptions made by the golf course managers. The difference in assumed fuel consumption was due to different machinery being used for aeration. Data on fuel consumption for verticutting and dressing were based on measurements (Caple, 2008). Since a higher rate of sand was applied to tees and fairways in Uppsala, higher fuel consumption per hectare was assumed for these areas compared with dressing of the greens, based on estimates made by the course managers.

2.4. System boundaries

The system studied included production of purchased inputs (fertiliser, fuel and electricity), transport of sand, production, maintenance and repair of machinery, and turf management for different activities according to current practices during one representative year (Fig. 1). Fuel consumption per maintenance cycle included travelling between courses parts for the machinery in use.

The contribution from production and application of herbicides and fungicides was omitted in the assessment, since it contributed less than 1% to the total energy use and GHG emissions. Reseeding was also omitted, since its contribution was considered negligible.

Construction of the courses was not included due to lack of information about the resources used during construction, as it was performed many decades ago.

A considerable amount of clippings is either composted, spread out directly on other grassed areas or left on-site after mowing. The emissions of N_2O associated with turnover of these clippings were considered in the sensitivity analysis, since high variability can be expected and no measurements were available. Indirect emissions of N_2O caused by N losses through volatilisation and leaching were not accounted for, since these emissions were considered minor compared with the direct emissions of N_2O.

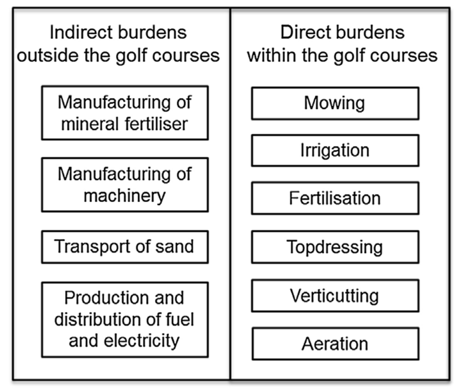

Fig. 1. Activities included in the study causing direct and indirect energy use and GHG emissions within and outside the golf courses.

2.5. General assumptions and data used

Data on GHG emissions from fuel combustion relating to transport and maintenance operations were taken from Gode et al. (2011) and included production, distribution and combustion. Only emissions data for standard diesel were used, although also synthetic diesel was used for some applications. Electricity consumption for irrigation was estimated by the course managers to be 0.45 kWh m^{-3} at Uppsala and 0.5 kWh m^{-3} at Sigtuna. Emissions data for the Swedish average electricity production were taken from Gode et al. (2011), assuming an electricity mix primarily based on nuclear power and hydropower. A factor of 2.1 was used for converting electricity into primary energy, considering a transformation efficiency of 50% and distribution losses in the grid. In the sensitivity analysis, the impact of electricity produced from natural gas was evaluated as an alternative to prevailing production conditions in Sweden.

Different machines and devices are used on golf courses for the many management operations performed. A thorough inventory of all machinery used, its material composition, annual use, life-time etc. was not possible due to lack of site-specific information from the golf courses. Instead, a rough estimate was made by assuming that energy use and GHG emissions from manufacturing, maintenance and repair of machinery comprised 17% of the total energy use and GHG emissions from all turf operations performed. This estimate was based on the distribution between manufacturing and operation phases calculated for Swedish crop production in the same region (Tidåker et al., 2016). The engine oil and hydraulic oil used were assumed to be included in this estimate.

Data on energy use for fertiliser production were taken from Brentrup and Pallière (2008), based on average figures for European production in 2006, while data on GHG emissions were taken from Kool et al. (2012). Data for urea ammonium nitrate were chosen, since the fertiliser products used contained a mixture of urea, ammonium and nitrate. The average diesel requirement for transport of sand was set at 0.4 L km^{-1}, assuming a truck and trailer with empty return transport.

Table 3
Frequency of annual maintenance cycles performed on different parts of the golf courses in Sigtuna and Uppsala.

	Site	Mowing	Aeration	Verticutting	Topdressing
Green	Sigtuna	160	6	14	14
	Uppsala	198	6	8	13
Tee	Sigtuna	88	1	3	3
	Uppsala	82	6	0	1
Fairway	Sigtuna	88	2	0	0
	Uppsala	82	3	0	1

Table 4
Fuel consumption (litres ha^{-1} $occasion^{-1}$) during management operations on different parts of the golf courses in Sigtuna and Uppsala.

		Mowing	Aeration	Verticutting	Topdressing
Green	Sigtuna	3.3	42	11	8.7
	Uppsala	3.6[a]	42	11	8.7
Tee	Sigtuna	8	42	11	8.7
	Uppsala	10.5	21		18
Fairway	Sigtuna	3	9		
	Uppsala	3.2[b]	9		18

[a] On the main course, 188 mowing operations were performed using a pedestrian mower (3.6 L petrol ha^{-1}), and 10 operations were performed using a ride-on mower (7.1 L diesel ha^{-1}).
[b] Mean fuel consumption included the assumption that half the mowing regimes were performed with a groomer with higher diesel use.

Direct emissions of N_2O from soils were estimated using the IPCC default emissions factor (2006), which is 1% of the total N added as mineral fertiliser. In the sensitivity analysis, this emissions factor was applied to the grass clippings.

3. Results

3.1. Energy use per hectare of green, tee, fairway and rough

Energy use was highest for greens, followed by tees and fairways (Table 5). Energy use for green management was roughly three times higher per hectare than for fairways on the same golf course. The lowest energy use was associated with maintenance of rough (7.6 GJ for Sigtuna and 7.1 GJ for Uppsala), which only included mowing and manufacture and maintenance of machinery. Mowing was the single most energy-consuming activity performed for all types of areas. However, the contribution from mowing per hectare was less than half of all energy use (26–45%) associated with maintenance of green, tee and fairway, since irrigation and manufacturing of mineral fertiliser in particular made important contributions. For greens, transport of sand added significantly to the total energy use.

Energy use for maintenance of fairways was considerably higher for Uppsala, which was largely explained by the higher application rate of N fertiliser and sand transport over a longer distance.

3.2. Emissions of GHG per hectare of green, tee, fairway and rough

Emissions of GHG from maintenance of one hectare of green were 6.2 Mg CO_2e for Sigtuna and 6.8 Mg for Uppsala (Fig. 2). Among management activities, mowing contributed most to GHG emissions (23% for Sigtuna and 27% for Uppsala). A major source of GHG emissions was associated with mineral fertiliser (in particular N), both through manufacturing, in which CO_2 and N_2O is released, and through emissions of N_2O from soil after application. In total, mineral fertiliser accounted for 38% of the GHG emissions at Sigtuna and 32% at Uppsala. For Uppsala, the contribution from transport of sand was also considerable.

Emissions of GHG from tees amounted to 4.7 and 6.1 Mg CO_2e ha^{-1} $year^{-1}$ for Sigtuna and Uppsala, respectively. These emissions were dominated by mowing (41 and 39% for Sigtuna and Uppsala, respectively), followed by manufacturing of mineral fertiliser, direct soil emissions (N_2O) and irrigation. Manufacturing of mineral fertiliser and soil emissions of N_2O after application accounted for 41% at both sites.

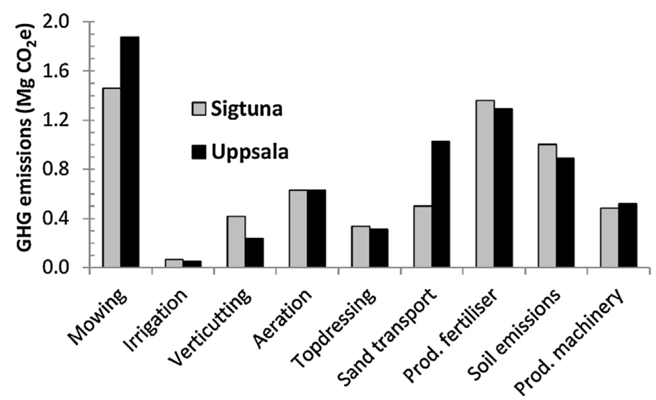

Fig. 2. Emissions of GHG (kg CO_2e ha^{-1} $year^{-1}$) divided into different maintenance activities for greens at the golf courses in Sigtuna and Uppsala.

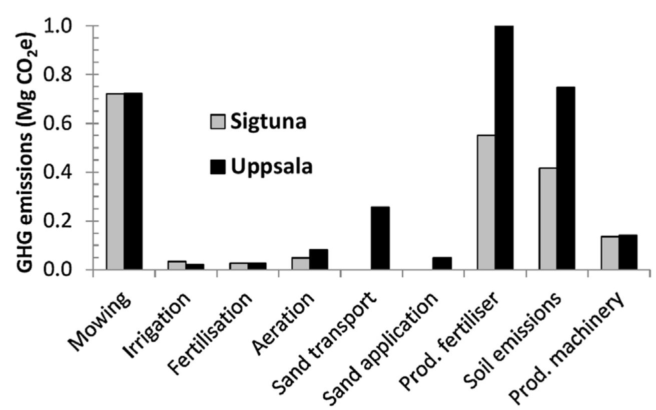

Fig. 3. Emissions of GHG (Mg CO_2e ha^{-1} $year^{-1}$) divided into different maintenance activities for fairways at the golf courses in Sigtuna and Uppsala.

Emissions of GHG associated with maintenance of fairways differed greatly between the sites and were 1.9 Mg CO_2e ha^{-1} $year^{-1}$ for Sigtuna and 3.1 Mg CO_2e ha^{-1} $year^{-1}$ for Uppsala (Fig. 3). A considerable share of the GHG emissions was related to mineral fertiliser, including both the fertiliser manufacturing phase and soil

Table 5
Primary energy use (GJ ha^{-1} year^{-1}) split into different maintenance activities for green, tee and fairway at the golf courses in Sigtuna and Uppsala.

	Green		Tee		Fairway	
	Sigtuna	Uppsala	Sigtuna	Uppsala	Sigtuna	Uppsala
Mowing	21	27	27	33	10	10
Irrigation	14	10	14	10	7	5
Verticutting	6	3	1			
Aeration	9	9	1	5	1	1
Topdressing	5	4	1	1		1
Transport of sand	7	15	2	4		4
Fertilisation					0.4	0.4
Mineral fertiliser production	13	13	10	14	5	10
Production of machinery	6	7	5	7	2	2
Total	81	89	61	74	25	33

Table 6
Relative contribution of different maintenance activities to total primary energy use and GHG emissions for the entire golf courses in Sigtuna and Uppsala.

	Energy use (%)		GHG (%)	
	Sigtuna	Uppsala	Sigtuna	Uppsala
Mowing	57	46	54	39
Irrigation	14	10	1	1
Verticutting	1	1	1	1
Aeration	3	4	3	3
Top dressing	1	2	1	1
Transport of sand	2	9	2	7
Production of mineral fertiliser	11	20	16	24
Direct soil emissions			12	17
Production of machinery	11	9	10	7
Total per ha & year	100	100	100	100

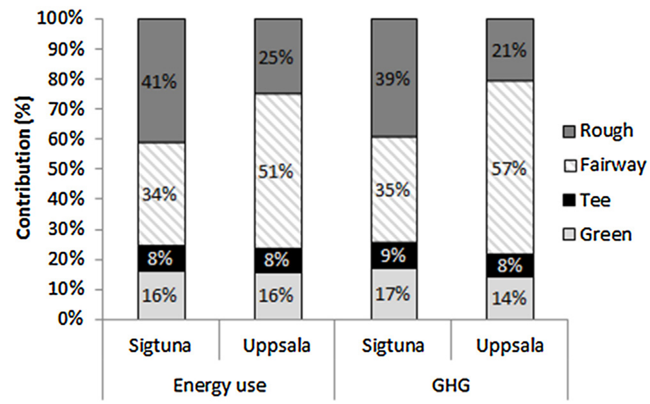

Fig. 4. Relative contribution to primary energy use and GHG emissions split into green, tee, fairway and rough for the golf courses in Sigtuna and Uppsala.

emissions of N_2O occurring after application. In total, emissions relating to fertilisation were 50% for Sigtuna and 58% for Uppsala, while the corresponding figures for mowing were 37 and 23%, respectively.

The contribution to GWP per hectare from maintenance of roughs was 0.54 Mg CO_2e for Sigtuna and 0.50 Mg CO_2e for Uppsala. The only aspects accounted for were mowing and production of machinery.

3.3. Energy use and GHG emissions for the entire golf courses

For the golf courses studied, the largest proportion of area was occupied by rough, followed by fairway, green and tee. The results per hectare were therefore converted to values for the entire course in order to obtain information on how total energy use and GHG emissions are distributed between the different playing areas and which activities to prioritise in order to improve the overall environmental performance. In Table 6, energy use and GHG emissions are split into different activities expressed for the entire golf courses, using the areas presented in Table 1.

Mowing was by far the single most energy-consuming activity, and also made a major contribution to GWP (Table 6). Fertilisation affected both energy use and GHG emissions. Emissions of GHG relating to fertilisation (manufacturing and soil emissions) from Uppsala contributed considerably (41%) due to the higher N application rate on fairways and the higher proportion of fairway within the total area. The corresponding value for GHG emissions related to fertilisation at Sigtuna was 28%.

Expressed as area-weighted average per hectare and year for the entire golf courses, the energy use was 14 GJ for Sigtuna and 19 GJ for Uppsala. The corresponding contribution to GWP was 1.0 and 1.6 Mg CO_2e, respectively.

Greens constituted a minor proportion of the golf courses (approximately 3%), but contributed a considerably larger share of the total energy use and GHG emissions (14–17%) due to their intensive management (Fig. 4).

The contribution to energy use and, in particular, to GHG was considerably higher for fairways than its share of the total area within golf courses (19% of the area at Sigtuna and 29% at Uppsala), while the extensively managed rough made a significantly lower contribution than its share of the golf courses (76% of the area at Sigtuna and 66% at Uppsala). For Sigtuna, rough was the area associated with the highest energy use and GHG emissions. For Uppsala, more than half of all energy use and GHG emissions was related to fairway management.

3.4. Sensitivity analysis

Emissions of GHG from electricity production are strongly influenced by its origin. The low carbon footprint from the Swedish electricity mix reflects its large share of hydropower and nuclear power, both associated with low GHG emissions. The assumption in the sensitivity analysis that the electricity used for irrigation was produced on the long-term European margin, i.e. considered to be produced from natural gas, increased the GHG emissions on average by 10% at Sigtuna and 8% at Uppsala. The highest relative increase was obtained for fairways at Sigtuna (Table 7).

Emissions of N_2O were accounted for by assuming that 1% of the N applied as fertiliser was emitted as N_2O—N. However, grass clippings from golf course surfaces are either removed and composted, spread on other surfaces or left on-site. During decomposition of these clippings, N_2O will be emitted. According to model simulations of N_2O emissions from urban lawns, expected N_2O—N losses range between 0.75–3.57 kg ha^{-1} year^{-1} for lawns fertilised with 0–89 kg N, and recycling of lawn clippings has been identified as an important source of N_2O emissions (Gu et al., 2015). The proposed default emissions factor for N_2O—N according to IPCC (2006) for composting in windrows with infrequent turning for mixing and aeration is 1%. This is within the same order of magnitude as

Table 7
Emissions of GHG (Mg CO_2e ha^{-1}) on changing the assumptions as regards electricity mix, N_2O emissions from decomposition of grass clippings and soil carbon sequestration in the sensitivity analysis.

	Green		Fairway		Rough	
	Sigtuna	Uppsala	Sigtuna	Uppsala	Sigtuna	Uppsala
Original setting	6.2	6.8	1.9	3.1	0.5	0.5
Electricity from natural gas	6.9	7.4	2.3	3.4		
Including N_2O from clippings	6.9	7.2	3.5	4.9	1.3	1.4
Including C sequestration			0.8	2.0	−0.6	−0.6

the value reported for garden waste composting in Danish studies (Boldrin et al., 2011). An emissions factor of 1% was used in the sensitivity analysis in the present study, irrespective of how the grass clippings were handled. The N content in clippings, information required for estimating N_2O emissions, was not measured within this study. However, data on net primary production (NPP) of above-ground biomass for the different management areas on the golf courses in Sigtuna and Uppsala were available in another study within the same research programme estimating NPP through frequent sampling during the growing season in 2014 (unpublished data). That study showed that NPP was significantly lower in greens (4.5 and 2.7 Mg dry matter ha^{-1} in Sigtuna and Uppsala, respectively) than in fairways and roughs, but did not differ significantly between fairways and roughs and was on average 11.5 Mg dry matter ha^{-1} in Sigtuna and 12.5 Mg ha^{-1} in Uppsala. Accumulated N uptake in clippings was assumed to correspond to 3% of NPP, which is a rather conservative estimate of the N concentration in frequently cut turfgrass clippings (e.g. Kopp and Guillard, 2002) and is considered the limit for achieving functioning and healthy looking turf in Sweden (Ericsson et al., 2012). In the unfertilised rough, the N concentration in clippings was assumed to be lower (1.5% of NPP) due to less frequent cuttings, as also reported for more mature grass swards in Sweden (Kätterer et al., 1998). As shown in Table 7, inclusion of N_2O from decomposition of clippings had a strong impact on GHG emissions from fairway and rough.

Soil organic C stocks are generally higher in grassland soil than in arable soil (Poeplau and Don, 2013). Since the golf courses studied here were established on arable land, which probably had a history of mixed farming, it is likely that C stocks in the turf have increased since establishment of the golf courses about 50 years ago. The topsoil (0–20 cm depth) in the fairway and rough areas currently contains about 80 Mg C ha^{-1} on average over the two sites (unpublished data), which is 23% more than the C content in mineral agricultural topsoils in the region (Andrén et al., 2008). If this difference in C storage is attributed to turf management over 50 years, soil sequestration in fairway and rough areas would amount to 0.3 Mg C ha^{-1} $year^{-1}$. Thus including soil C sequestration reduced the GHG emissions from fairways considerably and turned roughs into a sink for GHG.

4. Discussion

Energy use and GHG emissions per hectare were considerably higher from greens and tees than from fairways and, in particular, from extensively managed roughs (Table 7). For example, GHG emissions from greens were about two- and three-fold higher than those from fairways at Uppsala and Sigtuna, respectively. Bartlett and James (2011) reported similar differences between greens and fairways in their study on turf management at two British golf courses. Emissions of GHG per hectare from fairways at Sigtuna were of the same magnitude as reported for British parkland courses, while emissions from fairways at Uppsala were about 60% higher. Emissions of GHG per hectare from greens were slightly lower than reported for the British courses, while emissions from roughs were more than two-fold higher in the British study. However, there were some important differences in the maintenance activities performed in the different studies and in the processes included within the system boundary. Dressing, transport of sand and production of machinery were not included in the British study, which explains some of the differences. Moreover, the application rate of N mineral fertiliser and mowing frequency were higher for greens, tees and fairways on the Swedish golf courses included in this study. On the other hand, the GHG emissions from the British parkland rough were significantly higher due to N fertiliser application and high basal respiration (an aspect not included in this study). Emissions of GHG associated with the playing areas (tee, green, fairway and rough) in the study by Bartlett and James (2011), which amounted to 1.7 Mg CO_2e ha^{-1} $year^{-1}$ on average, were similar to those in Uppsala (1.6 Mg CO_2e ha^{-1} $year^{-1}$) but higher than those in Sigtuna (1.0 Mg CO_2e ha^{-1} $year^{-1}$). However, as emphasised above, the GHG emissions were distributed differently among the different playing components, in particular for the roughs.

Mowing made the single highest contribution to energy use for all areas. Introducing electrified machinery for some management operations would be an effective measure for reducing fossil fuel dependency and GHG emissions from golf turf management, provided that electricity is produced with renewable sources and a low carbon footprint.

Another important contributor to both energy use and GHG was mineral fertiliser, in particular N. Most GHG emissions were related to manufacturing of N mineral fertiliser, but N_2O emissions occurring after application also contributed considerably. Since the rather intensively managed fairways constitute a large part of golf courses, the environmental footprint for the entire golf courses was particularly determined by management of the fairways, especially for Uppsala. There was a marked difference in the N rate used on fairways at the two sites. Determining how the N application rate could be reduced on fairways while maintaining turf quality is thus an important step in reducing the environmental burden from golf courses. Assuming that a reduction in N application rate would also reduce turfgrass growth, the need for mowing, and thus the energy use and emissions related to mowing, would decrease.

Irrigation made an almost negligible contribution to GHG emissions due to the low GHG emissions associated with the current Swedish electricity mix. In regions where electricity is produced from natural gas, the contribution from irrigation would increase considerably, as shown in the sensitivity analysis. In regions where electricity is produced from coal, the carbon footprint from electricity would be even higher.

Intensive management, involving irrigation, mowing, fertilisation and recycling of grass clippings, are all activities associated with N_2O emissions (Gu et al., 2015). However, it is unclear how to account for N_2O emissions from grass clippings left for decomposition, since these emissions exhibit high temporal and spatial variability. The assumption in the sensitivity analysis that 1% of the N in grass clippings was emitted as N_2O—N strongly affected the GHG emissions from turf management. Handling of grass clippings is thus a potential hotspot within turfgrass management that needs further examination. Li et al. (2013) observed inconsistent responses when grass clippings were added in turfgrass systems, with soil aeration conditions as one important factor influencing the results. The grass clippings from fairways in Sigtuna and Uppsala were estimated to contain 345 and 375 kg N ha^{-1}, respectively, which made clippings an important source of N in the turfgrass system. Gu et al. (2015) advocate recycling of grass clippings as a means of lowering the N application rate. Exploiting the fertiliser value of recycled clippings in different conditions and reducing the application rates of mineral N fertilisation could be an effective management option for reducing N_2O fluxes from golf courses.

Soil C sequestration is an important measure to offset GHG emissions from turf management. An assumed soil C sequestration rate of 0.3 Mg ha^{-1} $year^{-1}$ for fairways and roughs in the present study resulted in a considerably lower carbon footprint for the Uppsala course (0.5 Mg CO_2e), while the GHG emissions from Sigtuna were totally eliminated. In a recent Swedish study, frequently cut urban lawns were found to contain 55% more soil C than surrounding arable soils (Poeplau et al., 2016). Perennial plants such as turfgrass generally have denser root systems than annual crops (Wang et al., 2014) and root-derived C is preferentially stabilised in soil (Kätterer et al., 2011). This is the main reason why an increased frequency of perennial forages in crop rotations (Bolinder et al., 2010) or a land use change from arable to permanent grassland leads to soil C sequestration (Kätterer et al., 2008). High C sequestration rates following conversion of farmland to golf courses have been reported in several studies. For example, Selhorst and Lal (2011) reported sequestration rates as high as 0.44 Mg C (corresponding to 1.6 Mg CO_2e) ha^{-1} $year^{-1}$ on average over a period of 91 years in fairway and rough areas on farmland converted to golf courses in Ohio. Even higher sequestration rates (0.9 and 1.0 Mg C ha^{-1} $year^{-1}$) were reported by Qian and Follett (2002) for fairways and greens on 16 golf courses in the USA. However, their study was more short-term (25–30 years) and this sequestration rate will probably not persist in a longer time perspective, since soil C sequestration rates are known to decrease with time until a new steady state soil C content is reached (Andrén and Kätterer, 2001). Compared with those values, the estimated sequestration rate for fairway and rough of 0.3 Mg C ha^{-1} $year^{-1}$ for our two Swedish sites was fairly low, although only slightly lower than the median C sequestration (0.42 Mg ha^{-1} $year^{-1}$) recorded in ley-arable rotations in 15 long-term field experiments under Nordic conditions (Kätterer et al., 2013). While the uncertainty in our estimates is high, since we had to rely on several assumptions due to lack of data, the higher sequestration rates for similar systems reported in the studies cited above suggest that our estimated sequestration rate of 0.3 Mg C ha^{-1} $year^{-1}$ is rather conservative and its inclusion in this LCA would not have overvalued the importance of soil C sequestration.

5. Conclusions

Energy use and GHG emissions per unit area were highest for greens, followed by tees, fairways and roughs. However, when considering the entire golf courses, both energy use and GHG emissions were mainly related to fairway and rough maintenance due to the larger area they occupied. Mowing was the most energy-consuming activity and contributed 21 and 27% of the primary energy use of the golf courses. Irrigation and manufacturing of mineral fertiliser and machinery also resulted in considerable energy use. Mowing and emissions associated with fertilisation (manufacture of N fertiliser and soil emissions of N_2O occurring after application) contributed most to GHG emissions. Emissions of N_2O from decomposition of grass clippings are a potential hotspot for GHG emissions from turf management that needs further investigation, since the high spatial and temporal variability of these emissions makes it difficult to estimate their actual contribution. Including the estimated mean annual soil C sequestration rate for fairway and rough in the assessment considerably reduced the carbon footprint for fairway and turned the rough into a sink for GHG. Appropriate measures for reducing energy use and carbon footprint from lawn management are thus: i) reduced mowing frequency when applicable, ii) investment in electrified machinery, iii) lowering the mineral N fertiliser rate (especially on fairways) and iv) reducing the amount and transport of sand for dressing. Lowering the mineral fertiliser rate is of particular importance, since GHG emissions originate from both the manufacturing phase and from N turnover after application. However, measures must be adapted to the prevailing conditions at the specific golf course and the requirements set by golfers. There is also a need for more golf courses that prioritise and market a low environmental footprint even at the expense of e.g. current aesthetic preferences. A life cycle perspective as applied in this study can be used as a tool for decision-support for golf courses aiming at improving their environmental performance.

Conflict of interest

We declare that no conflicts of interest of any kind (direct or indirect) exist.

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