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Are golf courses a source or sink of atmospheric CO_2: A modelling approach

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ABSTRACT

Sports facilities have been shown to have a positive impact on local biodiversity, quality of life and the economy. Their impact on global carbon balances is less clearly understood. Increased concentrations of atmospheric CO_2 have been linked with global climate change. Currently there is debate as to whether amenity turf is a net source or a net sink for atmospheric CO_2. The turfgrass of a natural sports pitch will sequester carbon through photosynthesis, but there are numerous emission sources associated with the management of turf which release CO_2 into the atmosphere. These include the engines used to power mechanised operations such as mowing and spraying, the application of agrochemicals, including fertilizers, and the disposal of waste.

In order to determine if a real-world example of a sports facility was a source or sink of carbon a mechanistic mass balance model was developed. Analysis indicated that, the areas of the golf course that received the most management attention were a net source of carbon emissions. The magnitude of these releases was significantly different on an equal area basis ($p<0.01$). The net carbon budget for turfgrass areas across the whole golf course, accounting for the sequestration by the turfgrass was -33.01 Mg C y^{-1}. The mature trees that formed an integral part of the landscape of the modelled course had a significant impact on the net carbon balance, resulting in overall net sequestration of -177.3 Mg C y^{-1} for the whole golf course, equivalent to -1.93 Mg C ha^{-1} y^{-1}. The variability in the size, shape and vegetation composition of different golf courses has a considerable impact on their net carbon balance, and the resultant environmental impact of sports facilities must be assessed on an individual basis.

1. INTRODUCTION

Natural sports turf has many roles in the landscape other than the primary function of their design for competition or recreation, including storing and cycling essential nutrients. Sports and amenity turf provide the capacity to sequester atmospheric carbon through soil organic carbon accumulation [**1, 2**] however mechanisation in the maintenance of turfgrass, and the application of synthetic fertilisers and agrochemicals, results in emissions of CO_2. Anthropogenic emissions of CO_2, have resulted in an estimated global temperature increase of 0.74 ± 0.18 °C in the last 100 years with an expected rise of at least 1.1 °C by the end of the 2050 [**3**]. The combustion of fossil fuels releases approximately 6.3 Pg C y^{-1}, while only 2.9 Pg C y^{-1} is sequestered by plants [**4**]. Political, public and economic pressures have increased on industries to account for, and reduce, carbon emissions at a global scale (*cf.* The Kyoto protocol and the Copenhagen agreement). Life cycle assessment (LCA) determines the contribution of a product or process to the anthropogenic release of carbon into the atmosphere as CO_2 (and other greenhouse gases) [**5**]; natural sports turf delivers its ‘product’ in terms of aesthetics and functionality for specific activities, rather than in terms of total output capacity.

Plants act as a sink for CO_2 by fixing carbon during photosynthesis and storing excess carbon as biomass in their leaves and roots. Managed turfgrass is commonly assumed to be a net sink for atmospheric CO_2 although these assumptions have recently been questioned [**6, 7**]. Other research has indicated that managed grassland areas in the UK lost soil carbon at a rate of 0.25 kg C m^{-2} y^{-1}, between 1978 and 2003 [**8**]. A recent study indicated that there had been no net change in carbon storage between 1982 and 2006 from long-term experimental grasslands which have been identically managed for over 100 years [**9**]. The accumulation of soil organic matter in managed sports turf systems has been shown to be greater than less-intensively managed grassland systems due to accelerated biogeochemical cycling from clipped leaf nitrogen and nitrogen fertiliser application [**1, 2**, **6**, **10**]; and sustained crop cover and reduced soil disturbance compared to agriculture [**11**]. The plants that make up a natural turf sports facility are capable of sequestering these emissions of CO_2 as part of the global carbon cycle.

This paper focuses on the balance of CO_2 emissions and sequestration in the turf grass system, as elemental carbon. The sequestration capacity of managed turf only represents one, relatively small, component of the whole-system C cycling on in sports turf. The use of mowing equipment, fertilisers and other agrochemicals, all cause emissions of CO_2, either directly during use and maintenance or during their manufacture [**11-13**]. A clear understanding of the role of amenity turf in the global carbon cycle and the dynamics of whole-system C balances are essential for informing the debate on overall sustainability in turfgrass management. To address this we pose two research questions:

1. What are the total annual C emissions from the maintenance of a natural sports turf, and how does this balance against a sports facilities capacity to sequester carbon?
2. How do C emissions vary for differently managed areas of sports turf, and how do the management techniques affect these emissions throughout the year?

2. METHODOLOGY

2.1. Model development

There are a wide range of operations or processes in the management of turfgrass that result in the release of CO_2 into the atmosphere. Therefore, to address the research questions, a mechanistic model of turfgrass maintenance was developed, and applied to sports turf in the context of a UK golf course. The system boundary for this model included emissions of C from mowing, agrochemical application, fertiliser application and irrigation. Emissions from the production of fertilizer and agrochemicals were also inside the system boundary. Any emissions that resulted from the manufacture of machinery used for maintenance or the construction of the golf course infrastructure were excluded and outside the system boundary.

The model was developed using principles similar to Dalgaard *et al.*, [**14**] and Ammann *et al.*, [**15**]. Based on a simple mass balance equation, emissions from maintenance are balanced against the turfgrass sequestration capacity for the whole golf course system (Equation 1). When the output from the model is positive, then there is a net release of carbon for the maintenance of the modelled turf area, where the value is negative, the grass is acting as a sink for atmospheric CO_2, with carbon stored within the system.

$$T = R - S \quad (1)$$

Where T is the total carbon efflux for an area of sports turf in g C m^{-2} y^{-1}, R is the carbon efflux from maintenance, defined by Equation 2, and S is the total carbon sequestered into the plant-soil system derived from analysis of soil organic matter accumulation in a study of golf courses soils in Colorado, USA [2]. The derived value is averaged across a range of soil types, previous land uses, grass species and other management practices, see Qian and Follet **[2]** for further details.

$$R = \sum a + \sum f + \sum i + \sum m \quad (2)$$

Where Σa is the sum of all the carbon released from the CO_2 emissions from the use and application of agrochemicals; Σf is the sum of the carbon released from the CO_2 emissions from the manufacture and use of fertilizer; Σi is the sum the carbon released from the CO_2 emissions associated with applying irrigation water; Σm is the sum of carbon released from all the CO_2 emissions associated with mowing. Constants for emissions of each component of the model were derived from a review of the literature (Table 1). The model uses the frequency of each maintenance operation described in Equation 2 on a monthly basis and the amount of chemicals used in the application of agrochemicals and fertilisers to determine the emissions from any area of natural turf. The model makes calculations over a fixed area, on a monthly basis, for the period of one year. Estimations of error were made using 10^6 Monte Carlo simulations for each of the input constants, assuming a standard deviation of 10% [**16-22**]. Where required, data were transformed to mass of elemental carbon using a standard conversion factor of 0.273, see Equation 3.

$$\frac{A(\mathrm{C})}{M(\mathrm{CO_2})} = \frac{12}{44} = 0.273 \qquad (3)$$

Where $A(\mathrm{C})$ is the atomic mass of carbon and $M(\mathrm{CO_2})$ is the molar mass of CO_2.

2.2. Golf course analysis

A private member, Parkland golf course (where the golf course is laid out among a wooded landscape) in Berkshire, UK was selected for analysis using the model described in Equations 1-3. This golf course had detailed historic records of their maintenance programme for each differently managed turfgrass area (in terms of increasing intensity of management: mown rough, fairways, tees, greens), from which all the input parameters required were derived (Table 2). Management data used for the modelling were taken from 2008, which represented an average climatic year, with annual rainfall of 657 mm and 1585 hours of sunshine compared to the preceding 10 year average (rainfall: 652 ± 39 mm; sunshine: 1636 ± 52 h). The area of different turf types was measured using aerial photographic interpretation. Each different turf type was managed using different machinery with differing fuel consumptions and engine oil capacities. Greens and tees were modelled using pedestrian mowers; fairways and mown roughs were modelled using self-propelled machinery with larger engines, fuel and oil consumptions [**23**]. All maintenance machinery used at this golf course is replaced on a rolling five year cycle.

Differences between areas of the golf course that were modelled were compared using one-way ANOVA. All modelling and data analysis was carried out using MATLAB 7.7 (MathWorks Inc., Cambridge, UK).

3. RESULTS & DISCUSSION

Each area of the golf course had significantly different CO_2 emissions from maintenance on an equal area basis ($p<0.01$, Table 3a). The greens accounted for 2.7 times the emissions of the mown rough areas, as result of the differences in the use of nitrogen fertiliser and increased mowing frequency (Table 2). The difference in the emissions between the tees and the fairways was also smaller by comparison to the rough (Table 3a). The increased intensity of these management inputs, typified by the amount of N fertiliser used, showed a strong linear relationship with the mean net C balance as would be expected for a linear model (Figure 1, $r^2 = 0.973$). In addressing our research questions, the model shows that there are significant differences in the emissions of carbon from maintenance on an equal area basis (Table 3a; $p<0.01$). These findings show that the management practices of different playing areas of a golf course are key in the scale of their capacity to sequester atmospheric carbon. These differences are directly related to their function and the management strategies that must be applied to them to achieve optimal playing conditions.

Analysis showed that when scaled to the areas of the whole golf course, the higher emissions from the tees and greens were diluted because of the relatively small proportions of the total area of the golf course that they occupy (Table 3b). The emissions per square metre of mown rough were considerably lower than the other land use types, but the nature of golf course design meant that this surface type was the dominant management feature. The lower intensity of management of this component of the golf course means that the rough is capable of sequestering 22.5 Mg C per year for this golf course. This surface type accounted for 31% of the area of the whole facility, and 53.6% of the total CO_2 emissions (Table 3b).

To analyse the relationships between management strategies and the CO_2 emissions, the output of the model was evaluated on a month-by-month basis. The cumulative emissions of each of the sum terms in Equation 2 are shown as stacked bars for each area of the golf course in Figure 2. The CO_2 emissions of each surface shows clear seasonal trends, because between April and September the grass grows more rapidly, and requires more intensive management to maintain playing quality. For all areas of the golf course, surfaces peaked as a net source for carbon emissions in either June or July (Figure 2).

For all surfaces, emissions from mowing dominated the monthly breakdown of the contributions to emissions, closely followed by fertilisers and agrochemicals. Management decisions, player perceptions and machinery efficiency all contribute to the carbon emissions associated with golf course maintenance. Advancement in mowing technology could result in considerable emissions reductions in the future. Figure 2 clearly highlights that the largest contributions to the emissions from the management came from mowing (Figure 2; $\sum m$). Plant growth shows seasonal patterns of above ground vegetative growth [**25, 26**], however the practice of mowing slowly growing or senescent turfgrass is carried out because in amenity turf management, cutting above-ground growth is only one function of mowing. Mowing is also used to condition and maintain the quality of the playing surface to achieve optimum function [**23**]. The specific approach that the golf course manager takes to maintaining the turf in terms of presentation determines the efficiency of mowing and the associated fuel usage [**20, 23**]. At the highest standard golf courses some golf course managers use the “double cutting” technique (Figure 3) to help maintain turfgrass health.

When turfgrass is consistently mown in one orientation the grass plant will respond by growing in the same orientation. This can lead to a reduction in playing quality of the turfgrass. Two passes with a mower, at right angles to a each other can help to prevent this problem occurring. This approach to mowing also produces the most commercially and aesthetically desirable chequered pattern to the turf grass (Figure 3b), such as the course modelled here. However, it requires the mower to cover twice the distance and to change direction 2.6 times more than for the most efficient mowing pattern (Figure 3). A reduction in mowing intensity of the greens of this golf course in line with the mowing pattern shown in Figure 3a would reduce the emissions from this area of the golf course by 35.3 g C m^{-2} y^{-1}, i.e. equivalent to more than the emissions of the mown rough area (Table 3a). Figure 2 also identifies that emissions may be reduced by reducing fertiliser inputs in late autumn, when the risk of leaching losses are high and plants uptake of nitrogen is low [**24**]. Reductions in fertiliser use at this time could therefore facilitate a reduction in emissions from tees and greens. Significant reductions could be achieved by educating players and media in the environmental consequences of aesthetic presentation.

The annual carbon budget for the whole golf course was calculated by scaling the mean emissions from each area of the golf course to the total area of that playing surface (Table 3b). Total CO_2 annual emissions for the managed turf areas of this golf course were estimated to be 10.75 Mg C y^{-1}, with a net carbon balance of -33.01 Mg C y^{-1}. In a life cycle analysis of winter wheat (*Triticum aestivum*) production in Europe, emissions were estimated to be 0.66 Mg C ha^{-1} y^{-1} [**27**], i.e. comparable to the emissions from the golf course greens (Table 3b). However, the total area of this feature of the golf course is only 1.4 ha, or 1.5% of the golf course area. The other, less intensively managed areas of the course compensate for the high emissions from this surface type.

Trees also sequester CO_2 from the atmosphere and store it as C in wood (-3 Mg C ha^{-1} cover y^{-1}; [**29**]). At this golf course, 52.1% (48.1 ha) of the facility was non-play areas, predominantly planted with mature woodland. This results in a significant impact on the net carbon balance for the whole golf course. Assuming that the majority of the trees are mature, and planted at a typical urban woodland density [**29**], they would provide an estimated annual sequestration rate of -144.3 Mg C y^{-1}. Therefore the whole golf course net carbon balance was -177.3 Mg C y^{-1}; equivalent to -1.93 Mg C ha^{-1} y^{-1} for the whole golf course. The emissions from the intensive management of the sports turf only accounts for 6% of the whole carbon budget for the total golf course area, with the remainder being sequestration. Therefore, this golf course functions as a sink in the carbon cycle on an annual basis. The golf course modelled sequesters more carbon than arable wheat production [**27**], but less than agro-forestry producing biomass for fuel by a factor of four [**29**]. The architecture and design of this golf course with the predominance of trees has a greater influence on the carbon budget for the golf course than the mechanisation of the management. This may not be the case for other golf courses or sports facilities which have smaller areas of tress. Amenity turfgrass facilities should aim to reduce emissions, regardless of their offset capacity however; well managed golf course design is instrumental in determining the benefit of sports turf over another form of land use.

The model has a number of constraints that are important when considering these results. Despite extensive sensitivity analysis, the model is limited by its lack of external validation, a common problem with this approach of life cycle assessment [**30**, **31**]. Research into carbon budgeting of urban and managed grasslands of the type modelled is significantly underrepresented in academic research [**32**], therefore there are relatively limited sources of validation data. Full validation will require both field and laboratory experimentation to determine if the predicted emissions for each process correspond to those suggested by the model. Further research is also required to validate the assumptions of sequestration rate of turf grass in the UK climate. The approach taken models the carbon budget of the maintenance of sports turf, and the constants within the model represent the emission of CO_2 as carbon. However, in terms of the impact of sports turf on global climate change, emissions of CO_2 only represent one of the sources of gaseous emissions from golf courses that have global warming implications. Other gases such as nitrogen dioxide and nitrous oxide (N_2O) – released from fertiliser use and methane (CH_4) from the decomposition of green waste play significant roles in global warming [**7**]. These gasses have a comparatively greater role in the greenhouse effect; N_2O has 298 times the global warming potential compared to CO_2 [**3, 21, 22**].

4. SUMMARY

Through the development of a simple mass balance model it has been possible to address the over-arching question of whether land managed for amenity turf, such as that of a golf course is a net source or sink of carbon in the atmosphere. The model shows that while the management of the turf grass on golf courses consistently results in a release of CO_2, the other features of the landscape of the golf course, including the turf grass itself, are instrumental in counter-balancing these releases.

The results of this modelling exercise are not sensibly extrapolated to determine a CO_2 balance for golf courses across the whole of the UK. Site specific factors, such as landscape, golf course architecture, and the specific management strategy for maintaining the golf course have been shown to have a considerable impact on the overall results of the model.

The area of trees varies between parkland courses and is dependent on landscape and other land-use pressures; this could result in less net sequestration than the golf course modelled here. The area of fine turf (sources), compared to the size and vegetative composition of the mown rough and other non play areas (sinks) will vary between courses. Even for courses that have similar landscape features, the standard of golf played on the course will have a strong effect on the specific management strategies and policies of the golf course manager. This in turn will impact on the size of the source of the emissions from turf grass management. Further research is required applying the model described here in a range of management scenarios, determining the influence of players perception on the net carbon balance of a golf course.

The position of a golf course in the landscape is also likely to have an influence on the net carbon balance. A coastal ‘Links’ style golf course, where the landscape typically has few trees and the vegetation of the non playing areas and ”out of bounds” areas are dominated by coastal sedges and grasses, are likely to be different from the findings reported here. The agrochemical inputs to this style of golf course, especially with regard to fertiliser use, are often lower than for parkland courses. Therefore, the carbon budget, and resultant environmental impact must be assessed on a course by course basis. Through careful management of the whole land area of a golf course, reduction of maintenance inputs could mean that natural sports turf can add further value to the landscape, beyond providing areas for recreation and sport.

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LIST OF NOTATION

A(C)	Atomic mass of elemental carbon
$M(CO_2)$	Molar mass of CO_2
R	Total carbon efflux from the maintenance of sports turf of a fixed area of sports turf (g C m^{-2} y^{-1})
S	Total carbon sequestration by the plant soil system on a fixed area of sports turf (g C m^{-2} y^{-1})
T	Total carbon efflux from a fixed area of sports turf (g C m^{-2} y^{-1})
Σa	Sum of carbon emissions from agrochemical applications to a fixed area of sports turf (g C m^{-2} y^{-1})
Σf	Sum of carbon emissions from fertiliser applications to a fixed area of sports turf (g C m^{-2} y^{-1})
Σi	Sum of carbon emissions from the use of irrigation water on a fixed area of sports turf (g C m^{-2} y^{-1})
Σm	Sum of carbon emissions from mowing operations for a fixed area of sports turf (g C m^{-2} y^{-1})

Table 1: Constants used to estimate the C emissions from each operation on the golf course. Values given as kg C per kg.

Operation	Herbicide [33]	Fungicide [33]	Insecticide [33]	Potable water [34]	Electricity [34]	Diesel [34, 35]	Petrol [34, 35]	Lubricant [36]	N [18]	P [18]	K [18]
$\sum a$	4.70	5.18	4.93	0.07		0.69		0.94			
$\sum f$						0.69		0.94	0.73	0.06	0.04
$\sum i$				0.07	0.15						
$\sum m$ (self propelled)						0.69		0.94			
$\sum m$ (pedestrian)							0.63	0.94			

Sources: [18] Kramer et al. (1999); [33] West and Marland (2002); [34] Defra (2009); [35] Aubé 2001; [36] Kanokkantapong et al. (2009).

Table 2: Annualised input parameters of each modelled area of turfgrass found on the golf course per metre square

	Golf course feature			
Input parameter	Rough	Fairway	Tee	Green
Mowing frequency (n)	29	48	104	135
Volume of irrigation water (L m^{-3})	0	0	205	260
Insecticide applications (n)	0	1	4	4
Herbicide applications (n)	0	0	2	6
Fungicide applications (n)	0	1	2	4
Number of fertiliser applications (n)	1	3	10	13
Nitrogen fertiliser (g m^{-2})	2.4	4.5	20.7	29.0
Phosphorous fertiliser (g m^{-2})	0.0	0.1	1.5	8.2
Potassium fertiliser (g m^{-2})	1.4	2.7	13.8	15.9

Table 3: Emission balances modelled across different areas of the golf course. a) CO_2 emission balances as elemental C from each different area of the golf course modelled on an equal area basis. b) Total contributions to emissions for the whole golf course, scaled by the area of each golf course feature. Model outputs show mean values from 10^6 Monte Carlo simulations, letters indicate homogenous groups ($p<0.01$).

a)

Model output	Golf course feature			
	Mown rough	Fairway	Tee	Green
CO_2 emissions (g C m^{-2} y^{-1})	20.4	29.0	47.7	55.4
C sequestration by turfgrass (g C m^{-2} y^{-1})	-100.0	-100.0	-99.9	-100.0
Mean net C balance (g C m^{-2} y^{-1})	-79.6 a	-71.0 b	-52.2 c	-44.5 d
Standard deviation	5.7	3.5	6.1	3.1

b)

Whole golf course analysis	Golf course feature			
	Mown rough	Fairway	Tee	Green
Area (ha)	28.3	13.3	0.8	1.4
CO_2 emissions (Mg C y^{-1})	5.77	3.84	0.38	0.76
Contribution to emissions (%)	53.6	35.7	3.5	7.2
Net C balance (Mg C y^{-1})	-22.53	-9.44	-0.42	-0.62

Figures

Fig 1:

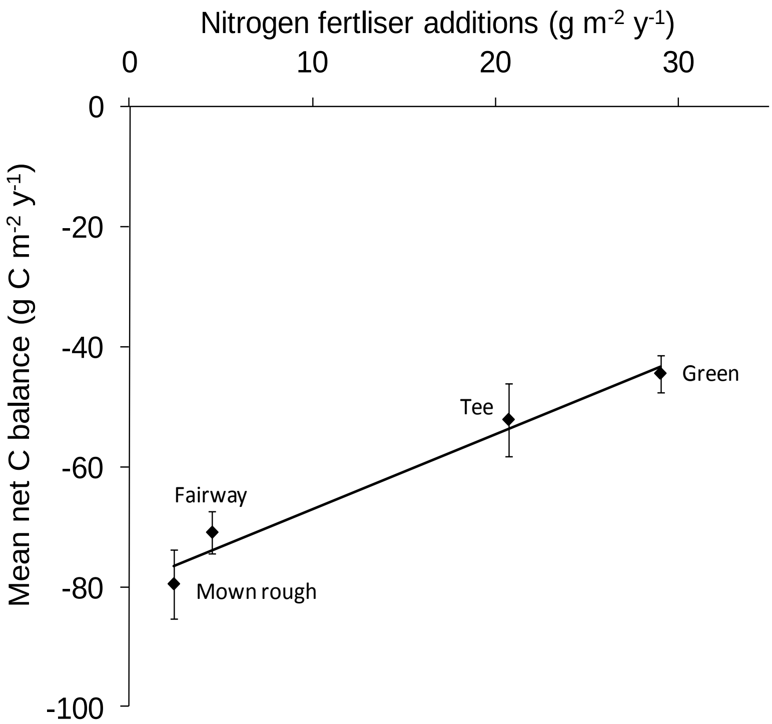

Fig. 1: Linear regression of annual nitrogen fertiliser additions with the mean net C balance for each area of the golf course, $p<0.01$, $r^2 = 0.973$.

Fig 2:

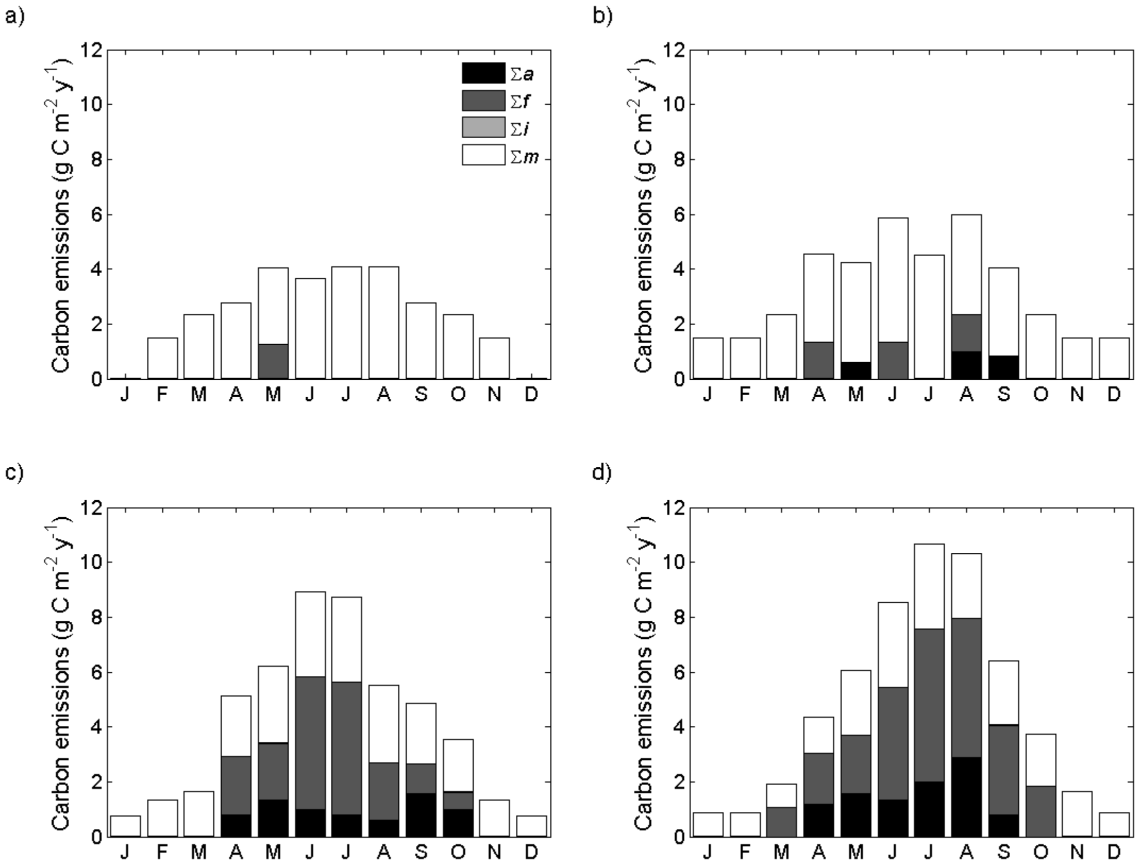

Fig. 2: Stacked bar chart showing the CO_2 effluxes from each individual area of the golf course a) mown rough; b) fairways; c) tees; d) greens for *Σm* is the sum of CO_2 emissions from mowing; *Σa* is the sum of CO_2 emissions from agrochemical applications; *Σf* is the sum of CO_2 emissions from fertilizer use; *Σi* is the sum of CO_2 emissions from irrigation. Letters indicate months of the year.

Fig. 3:

a) b)

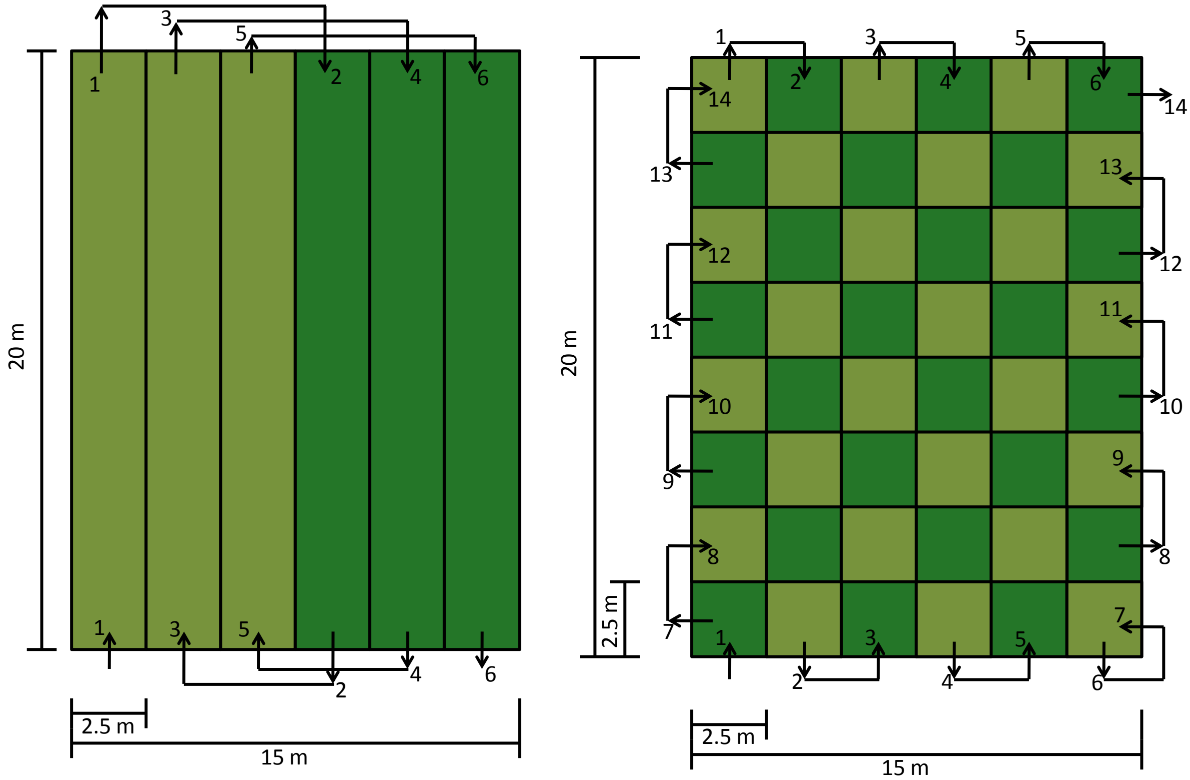

Fig 3: Schematic diagram shown two common approaches to mowing fine turfgrass. Arrows show direction of travel for the mower, numbers indicate the sequential passage of the mower. a) The most time and fuel efficient mowing pattern for a fixed area. b) "Double cutting" producing an aesthetically desirable checker-board effect.

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