

1 **Are golf courses a source or sink of atmospheric CO₂: A modelling approach**

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10 modelling; Mechanisation optimisation; Sustainability.

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12

13 **ABSTRACT**

14 Sports facilities have been shown to have a positive impact on local biodiversity, quality of
15 life and the economy. Their impact on global carbon balances is less clearly understood.
16 Increased concentrations of atmospheric CO₂ have been linked with global climate change.
17 Currently there is debate as to whether amenity turf is a net source or a net sink for
18 atmospheric CO₂. The turfgrass of a natural sports pitch will sequester carbon through
19 photosynthesis, but there are numerous emission sources associated with the management of
20 turf which release CO₂ into the atmosphere. These include the engines used to power
21 mechanised operations such as mowing and spraying, the application of agrochemicals,
22 including fertilizers, and the disposal of waste.

23

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

36

37 **1. INTRODUCTION**

38 Natural sports turf has many roles in the landscape other than the primary function of their
39 design for competition or recreation, including storing and cycling essential nutrients. Sports
40 and amenity turf provide the capacity to sequester atmospheric carbon through soil organic
41 carbon accumulation [1, 2] however mechanisation in the maintenance of turfgrass, and the
42 application of synthetic fertilisers and agrochemicals, results in emissions of CO₂.
43 Anthropogenic emissions of CO₂, have resulted in an estimated global temperature increase
44 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
45 the 2050 [3]. The combustion of fossil fuels releases approximately 6.3 Pg C y⁻¹, while only
46 2.9 Pg C y⁻¹ is sequestered by plants [4]. Political, public and economic pressures have
47 increased on industries to account for, and reduce, carbon emissions at a global scale (*cf.* The
48 Kyoto protocol and the Copenhagen agreement). Life cycle assessment (LCA) determines the
49 contribution of a product or process to the anthropogenic release of carbon into the
50 atmosphere as CO₂ (and other greenhouse gases) [5]; natural sports turf delivers its ‘product’
51 in terms of aesthetics and functionality for specific activities, rather than in terms of total
52 output capacity.

53

54 Plants act as a sink for CO₂ by fixing carbon during photosynthesis and storing excess carbon
55 as biomass in their leaves and roots. Managed turfgrass is commonly assumed to be a net sink
56 for atmospheric CO₂ although these assumptions have recently been questioned [6, 7]. Other
57 research has indicated that managed grassland areas in the UK lost soil carbon at a rate of
58 $0.25 \text{ kg C m}^{-2} \text{ y}^{-1}$, between 1978 and 2003 [8]. A recent study indicated that there had been no
59 net change in carbon storage between 1982 and 2006 from long-term experimental grasslands
60 which have been identically managed for over 100 years [9]. The accumulation of soil
61 organic matter in managed sports turf systems has been shown to be greater than less-

62 intensively managed grassland systems due to accelerated biogeochemical cycling from
63 clipped leaf nitrogen and nitrogen fertiliser application [1, 2, 6, 10]; and sustained crop cover
64 and reduced soil disturbance compared to agriculture [11]. The plants that make up a natural
65 turf sports facility are capable of sequestering these emissions of CO₂ as part of the global
66 carbon cycle.

67

68 This paper focuses on the balance of CO₂ emissions and sequestration in the turf grass
69 system, as elemental carbon. The sequestration capacity of managed turf only represents one,
70 relatively small, component of the whole-system C cycling on in sports turf. The use of
71 mowing equipment, fertilisers and other agrochemicals, all cause emissions of CO₂, either
72 directly during use and maintenance or during their manufacture [11-13]. A clear
73 understanding of the role of amenity turf in the global carbon cycle and the dynamics of
74 whole-system C balances are essential for informing the debate on overall sustainability in
75 turfgrass management. To address this we pose two research questions:

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

80

81 **2. METHODOLOGY**

82 **2.1. Model development**

83 There are a wide range of operations or processes in the management of turfgrass that result
84 in the release of CO₂ into the atmosphere. Therefore, to address the research questions, a
85 mechanistic model of turfgrass maintenance was developed, and applied to sports turf in the
86 context of a UK golf course. The system boundary for this model included emissions of C

87 from mowing, agrochemical application, fertiliser application and irrigation. Emissions from
88 the production of fertilizer and agrochemicals were also inside the system boundary. Any
89 emissions that resulted from the manufacture of machinery used for maintenance or the
90 construction of the golf course infrastructure were excluded and outside the system boundary.

91

92 The model was developed using principles similar to Dalgaard *et al.*, [14] and Ammann *et*
93 *al.*, [15]. Based on a simple mass balance equation, emissions from maintenance are balanced
94 against the turfgrass sequestration capacity for the whole golf course system (Equation 1).
95 When the output from the model is positive, then there is a net release of carbon for the
96 maintenance of the modelled turf area, where the value is negative, the grass is acting as a
97 sink for atmospheric CO₂, with carbon stored within the system.

$$98 \quad T = R - S \quad (1)$$

99 Where T is the total carbon efflux for an area of sports turf in $\text{g C m}^{-2} \text{y}^{-1}$, R is the carbon
100 efflux from maintenance, defined by Equation 2, and S is the total carbon sequestered into the
101 plant-soil system derived from analysis of soil organic matter accumulation in a study of golf
102 courses soils in Colorado, USA [2]. The derived value is averaged across a range of soil
103 types, previous land uses, grass species and other management practices, see Qian and Follet
104 [2] for further details.

$$105 \quad R = \sum a + \sum f + \sum i + \sum m \quad (2)$$

106 Where $\sum a$ is the sum of all the carbon released from the CO₂ emissions from the use and
107 application of agrochemicals; $\sum f$ is the sum of the carbon released from the CO₂ emissions
108 from the manufacture and use of fertilizer; $\sum i$ is the sum the carbon released from the CO₂
109 emissions associated with applying irrigation water; $\sum m$ is the sum of carbon released from
110 all the CO₂ emissions associated with mowing. Constants for emissions of each component of
111 the model were derived from a review of the literature (Table 1). The model uses the

112 frequency of each maintenance operation described in Equation 2 on a monthly basis and the
113 amount of chemicals used in the application of agrochemicals and fertilisers to determine the
114 emissions from any area of natural turf. The model makes calculations over a fixed area, on a
115 monthly basis, for the period of one year. Estimations of error were made using 10^6 Monte
116 Carlo simulations for each of the input constants, assuming a standard deviation of 10% [16-
117 22]. Where required, data were transformed to mass of elemental carbon using a standard
118 conversion factor of 0.273, see Equation 3.

$$\frac{A(C)}{M(\text{CO}_2)} = \frac{12}{44} = 0.273 \quad (3)$$

119 Where $A(C)$ is the atomic mass of carbon and $M(\text{CO}_2)$ is the molar mass of CO_2 .

120 **2.2. Golf course analysis**

121 A private member, Parkland golf course (where the golf course is laid out among a wooded
122 landscape) in Berkshire, UK was selected for analysis using the model described in Equations
123 1-3. This golf course had detailed historic records of their maintenance programme for each
124 differently managed turfgrass area (in terms of increasing intensity of management: mown
125 rough, fairways, tees, greens), from which all the input parameters required were derived
126 (Table 2). Management data used for the modelling were taken from 2008, which represented
127 an average climatic year, with annual rainfall of 657 mm and 1585 hours of sunshine
128 compared to the preceding 10 year average (rainfall: 652 ± 39 mm; sunshine: 1636 ± 52 h).
129 The area of different turf types was measured using aerial photographic interpretation. Each
130 different turf type was managed using different machinery with differing fuel consumptions
131 and engine oil capacities. Greens and tees were modelled using pedestrian mowers; fairways
132 and mown roughs were modelled using self-propelled machinery with larger engines, fuel
133 and oil consumptions [23]. All maintenance machinery used at this golf course is replaced on
134 a rolling five year cycle.

135

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

139 **3. RESULTS & DISCUSSION**

140 Each area of the golf course had significantly different CO₂ emissions from maintenance on
141 an equal area basis ($p < 0.01$, Table 3a). The greens accounted for 2.7 times the emissions of
142 the mown rough areas, as result of the differences in the use of nitrogen fertiliser and
143 increased mowing frequency (Table 2). The difference in the emissions between the tees and
144 the fairways was also smaller by comparison to the rough (Table 3a). The increased intensity
145 of these management inputs, typified by the amount of N fertiliser used, showed a strong
146 linear relationship with the mean net C balance as would be expected for a linear model
147 (Figure 1, $r^2 = 0.973$). In addressing our research questions, the model shows that there are
148 significant differences in the emissions of carbon from maintenance on an equal area basis
149 (Table 3a; $p < 0.01$). These findings show that the management practices of different playing
150 areas of a golf course are key in the scale of their capacity to sequester atmospheric carbon.
151 These differences are directly related to their function and the management strategies that
152 must be applied to them to achieve optimal playing conditions.

153

154 Analysis showed that when scaled to the areas of the whole golf course, the higher emissions
155 from the tees and greens were diluted because of the relatively small proportions of the total
156 area of the golf course that they occupy (Table 3b). The emissions per square metre of mown
157 rough were considerably lower than the other land use types, but the nature of golf course
158 design meant that this surface type was the dominant management feature. The lower
159 intensity of management of this component of the golf course means that the rough is capable

160 of sequestering 22.5 Mg C per year for this golf course. This surface type accounted for 31%
161 of the area of the whole facility, and 53.6% of the total CO₂ emissions (Table 3b).

162

163 To analyse the relationships between management strategies and the CO₂ emissions, the
164 output of the model was evaluated on a month-by-month basis. The cumulative emissions of
165 each of the sum terms in Equation 2 are shown as stacked bars for each area of the golf
166 course in Figure 2. The CO₂ emissions of each surface shows clear seasonal trends, because
167 between April and September the grass grows more rapidly, and requires more intensive
168 management to maintain playing quality. For all areas of the golf course, surfaces peaked as a
169 net source for carbon emissions in either June or July (Figure 2).

170

171 For all surfaces, emissions from mowing dominated the monthly breakdown of the
172 contributions to emissions, closely followed by fertilisers and agrochemicals. Management
173 decisions, player perceptions and machinery efficiency all contribute to the carbon emissions
174 associated with golf course maintenance. Advancement in mowing technology could result in
175 considerable emissions reductions in the future. Figure 2 clearly highlights that the largest
176 contributions to the emissions from the management came from mowing (Figure 2; $\sum m$).

177 Plant growth shows seasonal patterns of above ground vegetative growth [25, 26], however
178 the practice of mowing slowly growing or senescent turfgrass is carried out because in
179 amenity turf management, cutting above-ground growth is only one function of mowing.

180 Mowing is also used to condition and maintain the quality of the playing surface to achieve
181 optimum function [23]. The specific approach that the golf course manager takes to
182 maintaining the turf in terms of presentation determines the efficiency of mowing and the
183 associated fuel usage [20, 23]. At the highest standard golf courses some golf course
184 managers use the “double cutting” technique (Figure 3) to help maintain turfgrass health.

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

200

201 The annual carbon budget for the whole golf course was calculated by scaling the mean
202 emissions from each area of the golf course to the total area of that playing surface (Table
203 3b). Total CO_2 annual emissions for the managed turf areas of this golf course were estimated
204 to be $10.75 \text{ Mg C y}^{-1}$, with a net carbon balance of $-33.01 \text{ Mg C y}^{-1}$. In a life cycle analysis of
205 winter wheat (*Triticum aestivum*) production in Europe, emissions were estimated to be 0.66
206 $\text{Mg C ha}^{-1} \text{ y}^{-1}$ [27], i.e. comparable to the emissions from the golf course greens (Table 3b).
207 However, the total area of this feature of the golf course is only 1.4 ha, or 1.5% of the golf
208 course area. The other, less intensively managed areas of the course compensate for the high
209 emissions from this surface type.

210

211 Trees also sequester CO₂ from the atmosphere and store it as C in wood (-3 Mg C ha⁻¹ cover
212 y⁻¹; [29]). At this golf course, 52.1% (48.1 ha) of the facility was non-play areas,
213 predominantly planted with mature woodland. This results in a significant impact on the net
214 carbon balance for the whole golf course. Assuming that the majority of the trees are mature,
215 and planted at a typical urban woodland density [29], they would provide an estimated annual
216 sequestration rate of -144.3 Mg C y⁻¹. Therefore the whole golf course net carbon balance
217 was -177.3 Mg C y⁻¹; equivalent to -1.93 Mg C ha⁻¹ y⁻¹ for the whole golf course. The
218 emissions from the intensive management of the sports turf only accounts for 6% of the
219 whole carbon budget for the total golf course area, with the remainder being sequestration.
220 Therefore, this golf course functions as a sink in the carbon cycle on an annual basis. The
221 golf course modelled sequesters more carbon than arable wheat production [27], but less than
222 agro-forestry producing biomass for fuel by a factor of four [29]. The architecture and design
223 of this golf course with the predominance of trees has a greater influence on the carbon
224 budget for the golf course than the mechanisation of the management. This may not be the
225 case for other golf courses or sports facilities which have smaller areas of tress. Amenity
226 turfgrass facilities should aim to reduce emissions, regardless of their offset capacity
227 however; well managed golf course design is instrumental in determining the benefit of
228 sports turf over another form of land use.

229

230 The model has a number of constraints that are important when considering these results.
231 Despite extensive sensitivity analysis, the model is limited by its lack of external validation, a
232 common problem with this approach of life cycle assessment [30, 31]. Research into carbon
233 budgeting of urban and managed grasslands of the type modelled is significantly
234 underrepresented in academic research [32], therefore there are relatively limited sources of

235 validation data. Full validation will require both field and laboratory experimentation to
236 determine if the predicted emissions for each process correspond to those suggested by the
237 model. Further research is also required to validate the assumptions of sequestration rate of
238 turf grass in the UK climate. The approach taken models the carbon budget of the
239 maintenance of sports turf, and the constants within the model represent the emission of CO₂
240 as carbon. However, in terms of the impact of sports turf on global climate change, emissions
241 of CO₂ only represent one of the sources of gaseous emissions from golf courses that have
242 global warming implications. Other gases such as nitrogen dioxide and nitrous oxide (N₂O) –
243 released from fertiliser use and methane (CH₄) from the decomposition of green waste play
244 significant roles in global warming [7]. These gasses have a comparatively greater role in the
245 greenhouse effect; N₂O has 298 times the global warming potential compared to CO₂ [3, 21,
246 22].

247

248 **4. SUMMARY**

249 Through the development of a simple mass balance model it has been possible to address the
250 over-arching question of whether land managed for amenity turf, such as that of a golf course
251 is a net source or sink of carbon in the atmosphere. The model shows that while the
252 management of the turf grass on golf courses consistently results in a release of CO₂, the
253 other features of the landscape of the golf course, including the turf grass itself, are
254 instrumental in counter-balancing these releases.

255

256 The results of this modelling exercise are not sensibly extrapolated to determine a CO₂
257 balance for golf courses across the whole of the UK. Site specific factors, such as landscape,
258 golf course architecture, and the specific management strategy for maintaining the golf
259 course have been shown to have a considerable impact on the overall results of the model.

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

270

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

281

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286

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387

388 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)

389

390

391 **Table 1:** Constants used to estimate the C emissions from each operation on the golf course.

392 Values given as kg C per kg.

393

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			

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

396

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

399

Input parameter	Golf course feature			
	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

400

401 **Table 3:** Emission balances modelled across different areas of the golf course. a) CO₂
 402 emission balances as elemental C from each different area of the golf course modelled on an
 403 equal area basis. b) Total contributions to emissions for the whole golf course, scaled by the
 404 area of each golf course feature. Model outputs show mean values from 10⁶ Monte Carlo
 405 simulations, letters indicate homogenous groups (p<0.01).

406
 407

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

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b)

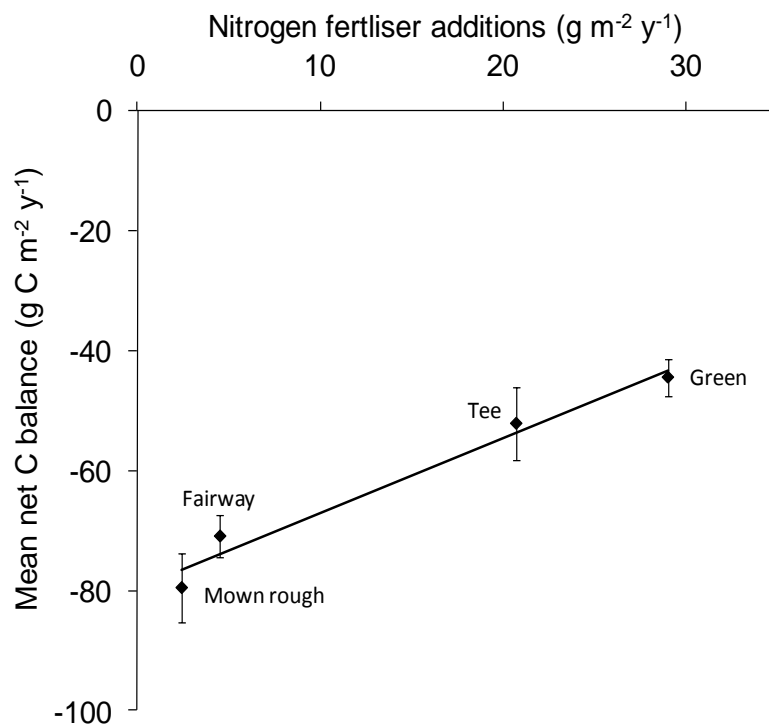
Whole golf course analysis	Golf course feature			
	Mown rough	Fairway	Tee	Green
Area (ha)	28.3	13.3	0.8	1.4
CO ₂ emissions (Mg C y ⁻¹)	5.77	3.84	0.38	0.76
Contribution to emissions (%)	53.6	35.7	3.5	7.2
Net C balance (Mg C y ⁻¹)	-22.53	-9.44	-0.42	-0.62

410
 411

412 **Figures**

413 Fig 1:

414



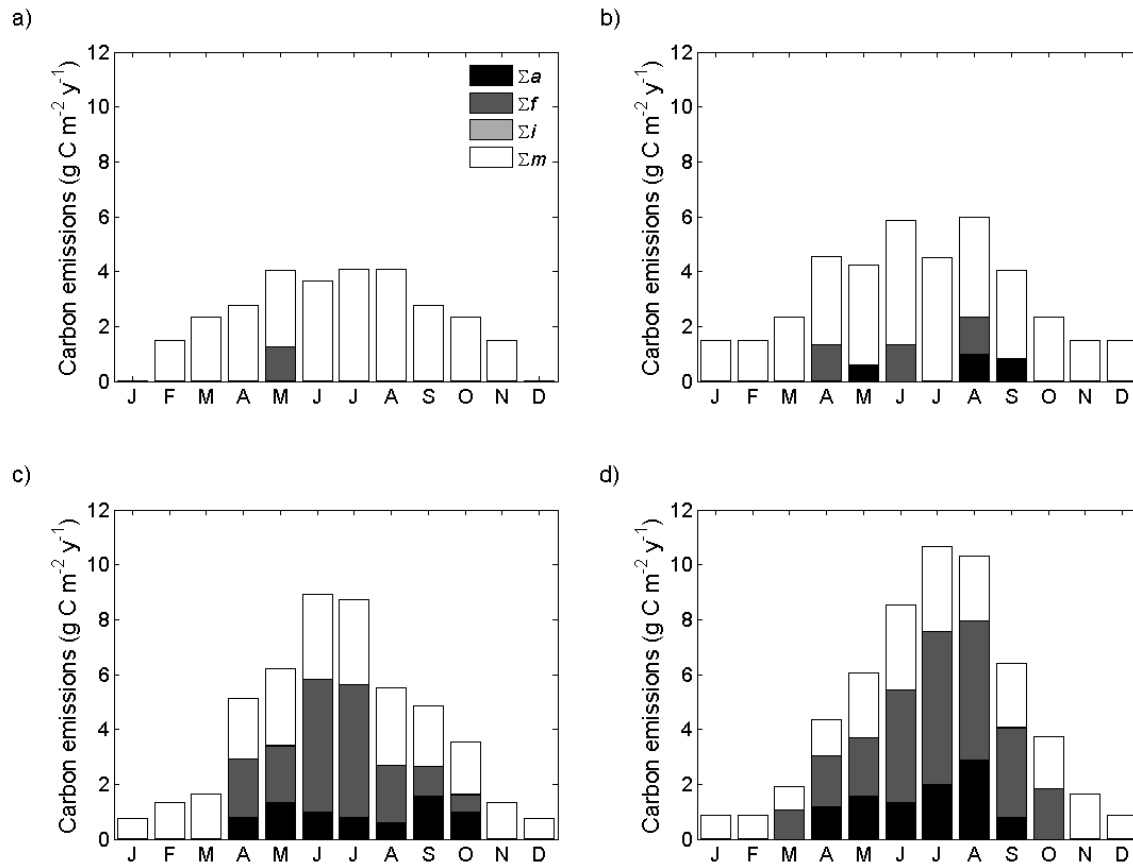
415

416

417 **Fig. 1:** Linear regression of annual nitrogen fertiliser additions with the mean net C balance

418 for each area of the golf course, $p < 0.01$, $r^2 = 0.973$.

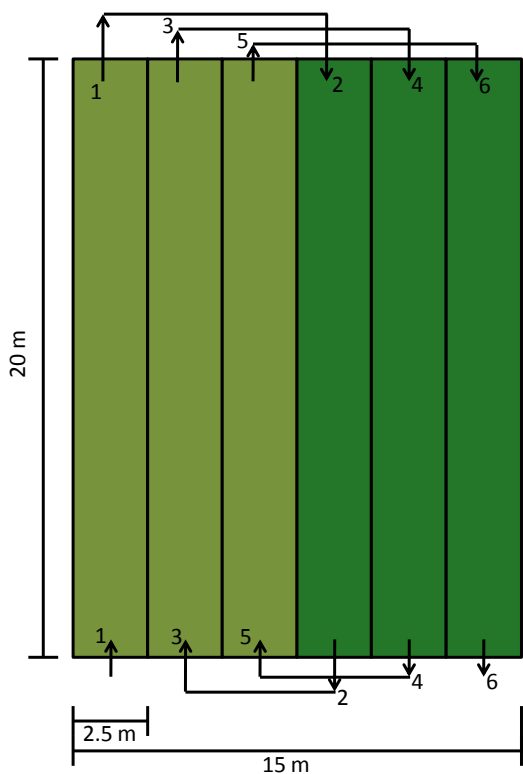
419 Fig 2:



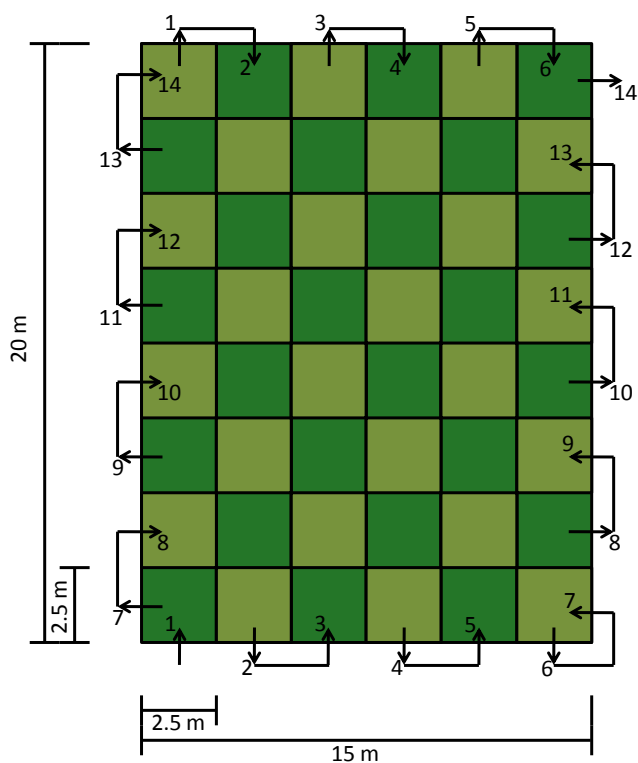
420
421

422 **Fig. 2:** Stacked bar chart showing the CO₂ effluxes from each individual area of the golf course a) mown rough; b) fairways; c) tees; d) greens
423 for Σm is the sum of CO₂ emissions from mowing; Σa is the sum of CO₂ emissions from agrochemical applications; Σf is the sum of CO₂
424 emissions from fertilizer use; Σi is the sum of CO₂ emissions from irrigation. Letters indicate months of the year.

425 Fig. 3:
426 a)



b)



426
427 **Fig 3:** Schematic diagram shown two common approaches to mowing fine turfgrass. Arrows
428 show direction of travel for the mower, numbers indicate the sequential passage of the
429 mower. a) The most time and fuel efficient mowing pattern for a fixed area. b) “Double
430 cutting” producing an aesthetically desirable checker-board effect.

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432