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GC2030 | University of St Andrews

Golf Course 2030

Soil Organic Carbon Storage in Coastal Golf Courses

Understanding Carbon Storage for Climate Positive Action in Golf Course Landscapes

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An introduction to carbon and climate.

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Soil organic carbon as a nature-based solution for climate positive actions in golf course landscapes.

What is soil organic carbon and why is it important?

All soils contain a measurable amount of soil organic matter, of which a significant component is held as organic carbon. While soil organic matter plays an integral role in soil functions, such as soil structure, nutrient and water retention, the organic carbon content of soils is also widely recognized as a significant global regulator of climate. This is because globally a large amount of carbon is stored as organic carbon in soils, approximately three times more than in the atmosphere. Therefore, sustainably managing soil carbon can contribute to land-based efforts to reduce carbon emissions, contribute to atmospheric carbon dioxide removal, and deliver ecosystem services which are nature positive.

Historical losses of carbon from soils, and particularly from agricultural soils, are well documented. While we may lack sufficient data to understand these changes in golf course landscapes, it almost certainly includes carbon losses resulting from common golf course soil management practices. In all cases, the added risks of future accelerated loss of soil carbon exists because of global warming.

Therefore, understanding soil organic carbon as a nature-based solution to strengthen the terrestrial carbon sink and to protect against further carbon dioxide emissions is essential, and offers new opportunities for climate positive actions in golf course landscapes.

Enhanced soil organic carbon storage

Strategies that help to protect existing soil organic carbon stocks (by avoiding losses where possible) and to restore soil organic carbon stocks (where these have been depleted) can deliver climate benefits as part of the global carbon budget. Such actions, while they need to be balanced against overall greenhouse gas emissions (such as carbon dioxide, methane, and nitrous oxide) from golf course landscapes represent emerging opportunities within and aligned to the United Nations Sustainable Development Goals (SDGs), and, as managed land, the United Nations Framework Convention on Climate Change (UNFCCC).

While it is likely that there will remain considerable uncertainty and debate around actionable pathways when it comes to golf (acknowledging for example green-management practices that serve to lower soil organic matter content to enhance playability), this report highlights an unquestionable opportunity to reevaluate soil organic carbon storage for climate positive action in golf course landscapes. Such actions are entirely compatible and to be encouraged as part of a wider and more sustainable approach to golf management practices; they should not be dismissed for golf, but neither should they be exaggerated.

Furthermore, there are additional benefits from these actions, such as maintaining or increasing resilience to climate change. The enhancement of soil organic carbon therefore generates opportunities to incentivise positive actions because existing policies in both the climate sector (primarily focused on climate mitigation) and agriculture (largely focused on soil health) are widely accepted as no-regrets pathways across a range of international conventions with multiple benefits for a more sustainable future.

How to use this report

This report sets out a methodology that was implemented as part of a project commissioned by the R&A within the GC2030 initiative; the work was carried out by a research team at the University of St Andrews.

The report highlights that soil organic carbon storage in coastal golf courses is equivalent to many other terrestrial and coastal soil types where organic carbon stores are being actively managed. The golf courses of Scotland, England and Wales collectively hold a significant national (UK) store of soil carbon, and hold, on average (area for area), more carbon than arable farmland in the UK.

The report also highlights that these soil organic carbon stores are vulnerable to the effects of coastal erosion deriving from accelerating sea-level rise. The report therefore provides a new evidence-based argument to support the case for coastal protection to help prevent and reduce the loss of these vulnerable organic carbon stores.

Within golf course landscapes, the ground managed as rough, or fairway support the highest soil carbon densities and potentially offer the best opportunity for enhancement of the soil organic matter store; this may be possible without overly impacting on the playability of the game.

The report illustrates case study examples, outlining the approach, methodology and soil carbon assessments for individual golf courses and shows how these coastal golf courses are vulnerable to future sea-level rise and coastal erosion.

As such, the report provides a template which could be adopted more widely to understand current soil conditions, providing a baseline assessment against which to understand management actions to enhance long-term soil organic carbon storage as part of a series of climate positive actions recommended by the GC2030 initiative.

Golf course soil organic carbon.

UK and Republic of Ireland golf courses

Across the UK and Republic of Ireland there are 3535 golf courses; of these 516 are within 1km of the mean tidal level (MTL) and can be considered coastal. Of these there are 435 eighteen-hole courses, 52 nine-hole and 29 six-hole courses (Figure 1).

These coastal courses are geographically distributed across nations with 53 located in the Republic of Ireland and 463 in the United Kingdom (435 Scotland, England, and Wales, 28 Northern Ireland). The courses located in Scotland, England and Wales occupy an area of 204.4km^2 (Ordnance Survey Greenspaces). Data to estimate the area that golf courses occupy in Northern, and the Republic of Ireland are currently not available.

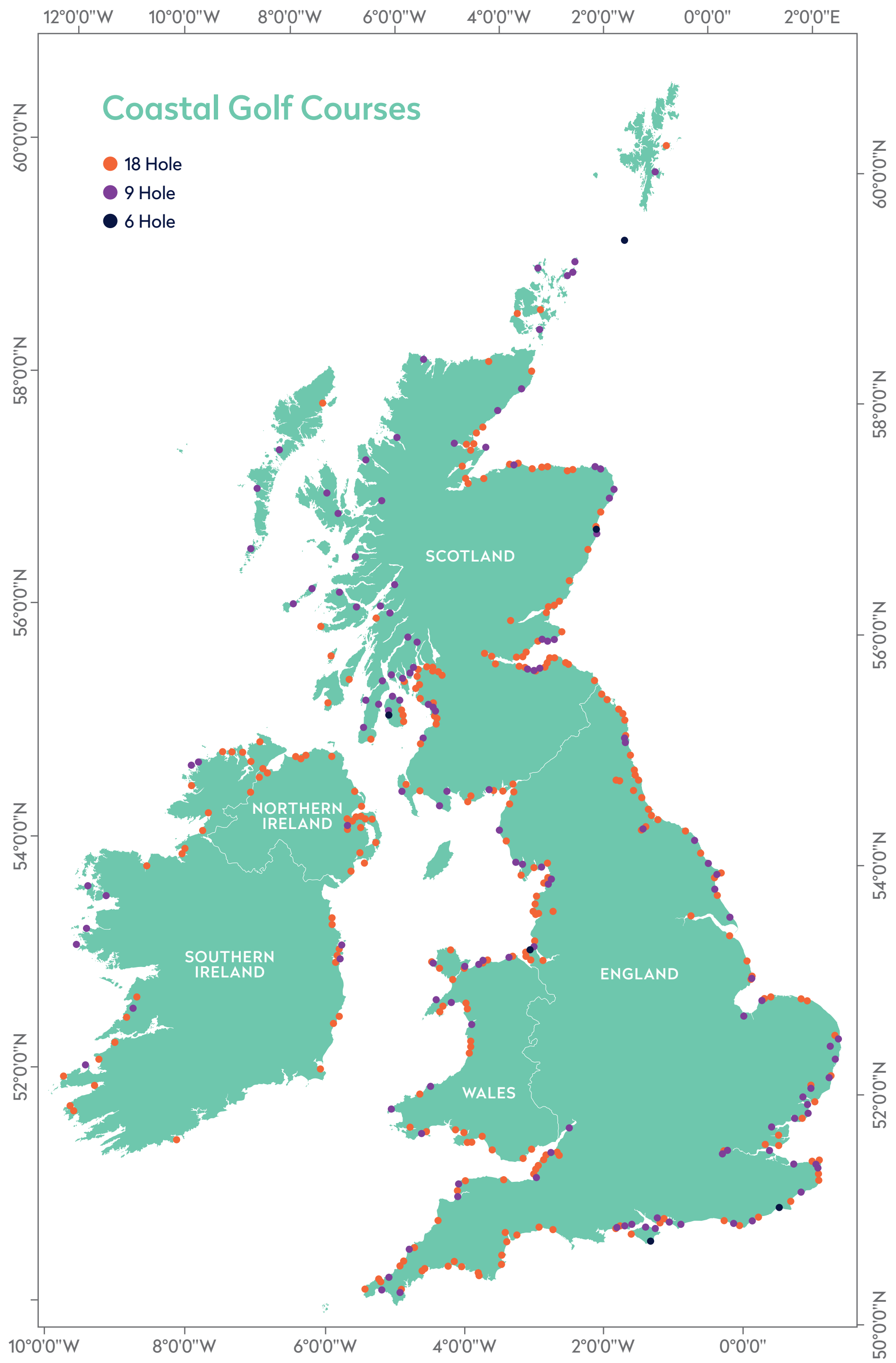

Figure 1. Coastal golf courses within the United Kingdom and Republic of Ireland. Coastal defined as within 1 km from the mean tidal level.

To determine the organic carbon stock, spatially consistent dry bulk density and organic carbon concentration data are required for all nations.

Quantifying soil organic carbon stocks

To quantify the organic carbon held within the soil of coastal golf courses across Scotland, England, and Wales a number of data sets need to be combined (Figure 2).

As discussed above, the extent of coastal golf courses were determined using the ordnance survey Greenspaces dataset which provides boundaries to golf courses in Scotland, England and Wales; this data is currently not available for Northern Ireland. To determine the organic carbon stock, spatially consistent dry bulk density and organic carbon concentration data are required for all nations. The Countryside Survey (Henrys et al., 2012) was carried out across the UK in 2007, topsoil (top 15cm) was collected and analysed to create gridded (1 x 1km) datasets for a number of variables including dry bulk density and organic carbon. Together these data facilitate the calculation of organic carbon storage (kg C m^{-2}) which when combined with areal extent of each golf course and soil depth (15cm) allows the soil (top 15cm) organic carbon stock to be determined. The Countryside Survey data (Henrys et al., 2012) does not fully encompass all coastal golf courses, the data cover 73.6% of courses leaving the remaining 26.4% unmapped.

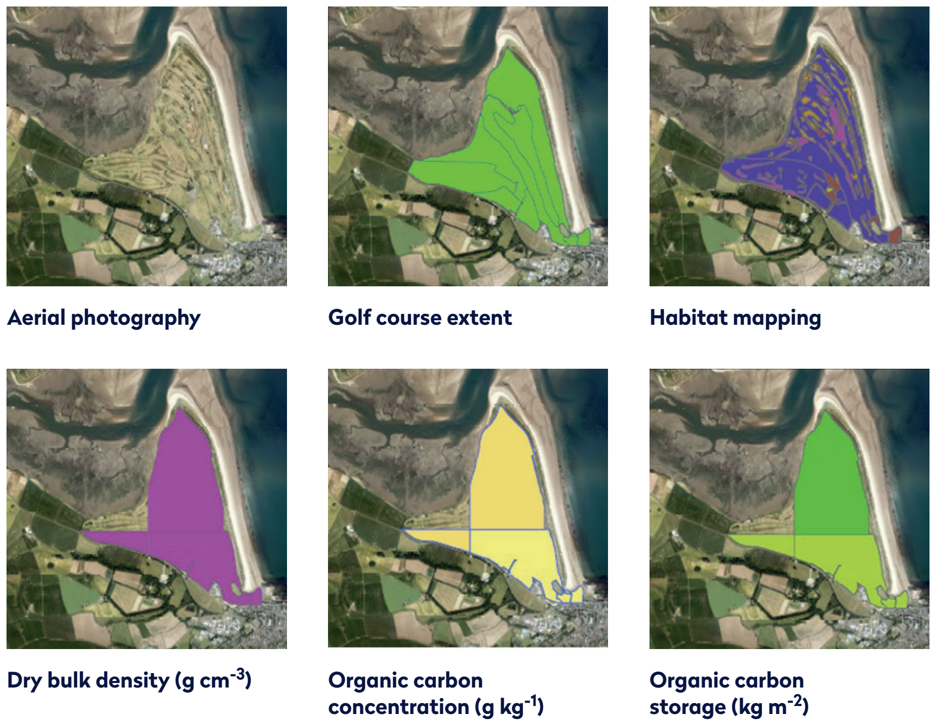

Figure 2. Workflow illustrating the data used to calculate the soil organic carbon stocks of coastal golf courses.

Organic carbon stocks of coastal golf courses

It is estimated that the mapped coastal golf courses in Scotland, England and Wales hold **1.02 ± 0.20 million tonnes of organic carbon** within the top 15cm of the underlying soil. The unmapped courses represent 26.4% of the total area of coastal golf courses and using the minimum and maximum dry bulk density and OC content data from across the mapped golf courses, it is estimate that between **0.18 and 0.42 million tonnes of additional organic carbon** is held within the 54km² of unmapped courses.

On average **6.8 ± 1.3kg C m^{-2}** is held within the top 15cm of soil in coastal golf courses which is less than the 9.5 ± 2.8kg C m^{-2} estimate to be held in the top 15cm of Scotland's coastal saltmarsh (Austin et al., 2021) and other non-grassland terrestrial landcover types (Figure 3). The quantity of organic carbon stored in coastal golf courses is comparable to neutral and improved grassland (Figure 3) which alongside arable land have lowest organic carbon values, ranging between 4.73 – 6.83kg C m^{-2} (Henrys et al., 2012).

These values represent an estimate of the organic carbon held in the soil and cannot be directly linked to carbon sequestration or climate change mitigation potential. The widespread use of fertiliser across golf courses (both natural and man-made) and green-management practices (lowering organic matter for playability) potentially results in soils being a net source of carbon dioxide to the atmosphere.

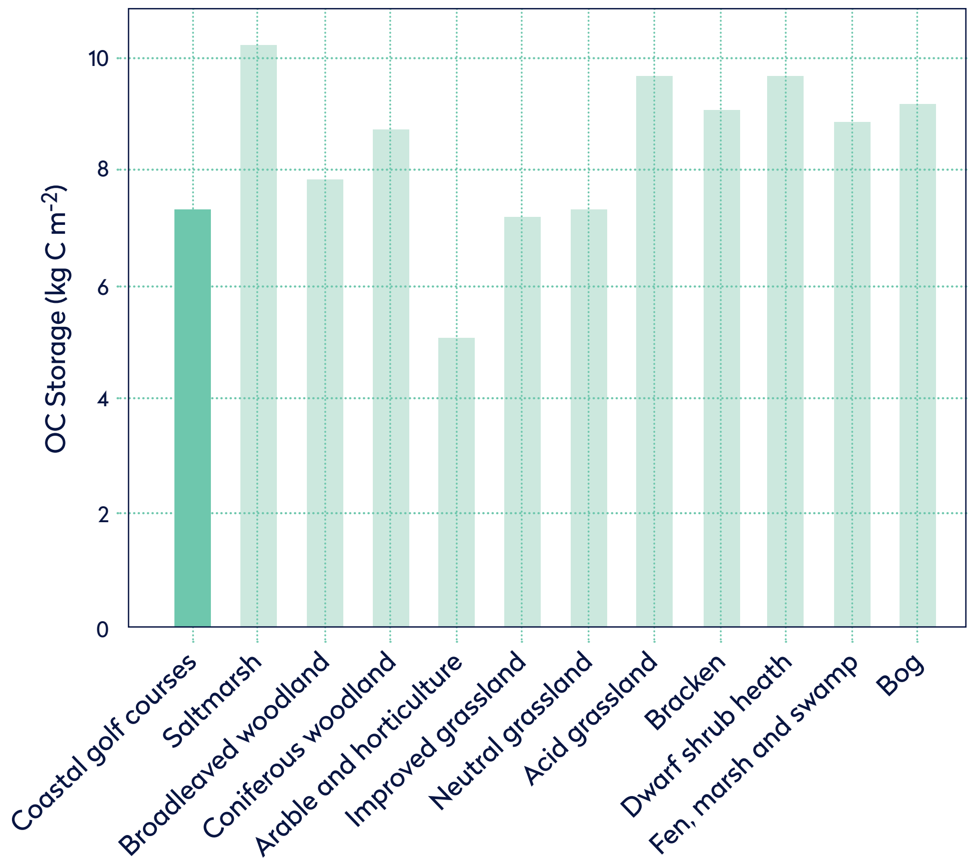

Figure 3. Soil (top 15cm) organic carbon storage in coastal golf courses in comparison to the organic carbon held within the top 15 cm of soil in Scottish saltmarshes (Austin et al., 2021) and terrestrial environments across the UK derived from the Countryside Survey data (Henrys et al., 2012).

Threats to coastal golf course soil organic carbon

The role of coastal golf course in the carbon cycle is highly complex and they are unlikely to have a major impact on climate because of significant sources of greenhouse gas emissions which counter soil organic carbon storage. However, there is a real possibility that the erosion of these sediments could lead to the transfer of organic carbon to the marine environment and its release to the atmosphere as carbon dioxide.

The most pressing threat to these coastal environments is rising sea levels which are predicted to continually rise to beyond the year 2100 (Howard et al., 2019; Figure 4). The rate of this rise is dependent on geographical location and future greenhouse gas emission scenarios. For example, under a low emissions scenario, the projected rise in sea level for the year 2300 is between 0.5 - 2.2m for London and 0.0 - 1.7m for Edinburgh, while the high emissions scenario, results in increases of 1.4 - 4.3m for London, and 0.7 - 3.6m in Edinburgh (Palmer et al., 2018).

The increase in sea level will lead to the erosion and loss of the current shoreline and will result in the transport of organic carbon from coastal soils including those in golf courses to the adjacent marine environment. During transport, soil organic carbon will be degraded by a variety of physical and biogeo-chemical process (Arndt et al., 2013) resulting in the loss of organic carbon to the atmosphere as carbon dioxide.

By managing golf courses as part of the wider coastal soil resource to prevent and reduce the loss of organic carbon to the wider marine environment will in turn avoid additional carbon dioxide emissions in the coming decades.

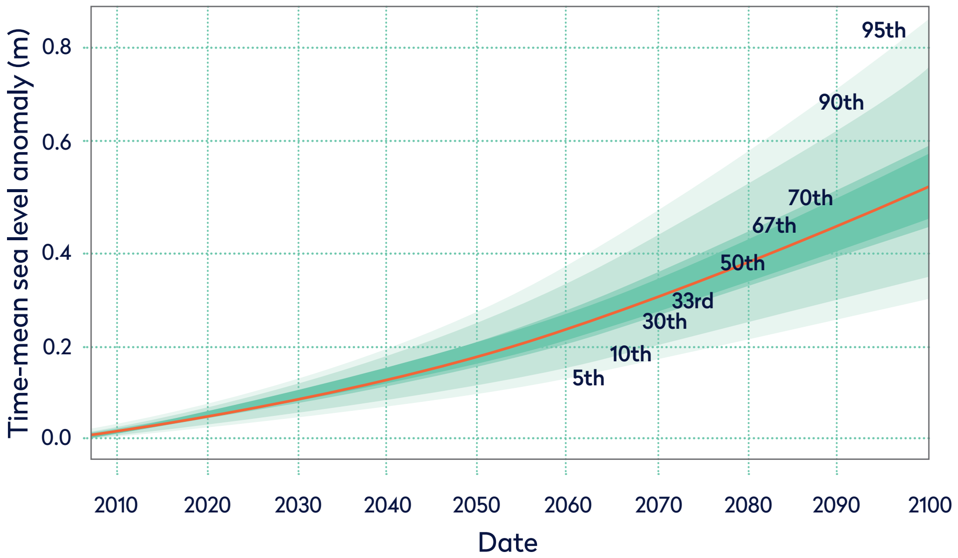

Figure 4. Projected sea level increase up to 2100 for St Andrews calculated using the high emission scenario (RCP8.5) data accessed from the UK climate projections portal operated by the Met Office **(https://ukclimateprojections-ui.metoffice.gov.uk/)**.

Case studies.

Aim

Across England, Scotland, and Wales soil samples were collected from eleven coastal golf courses (Figure 5) with the aim to directly measure soil properties and produce examples of site-specific organic carbon assessments.

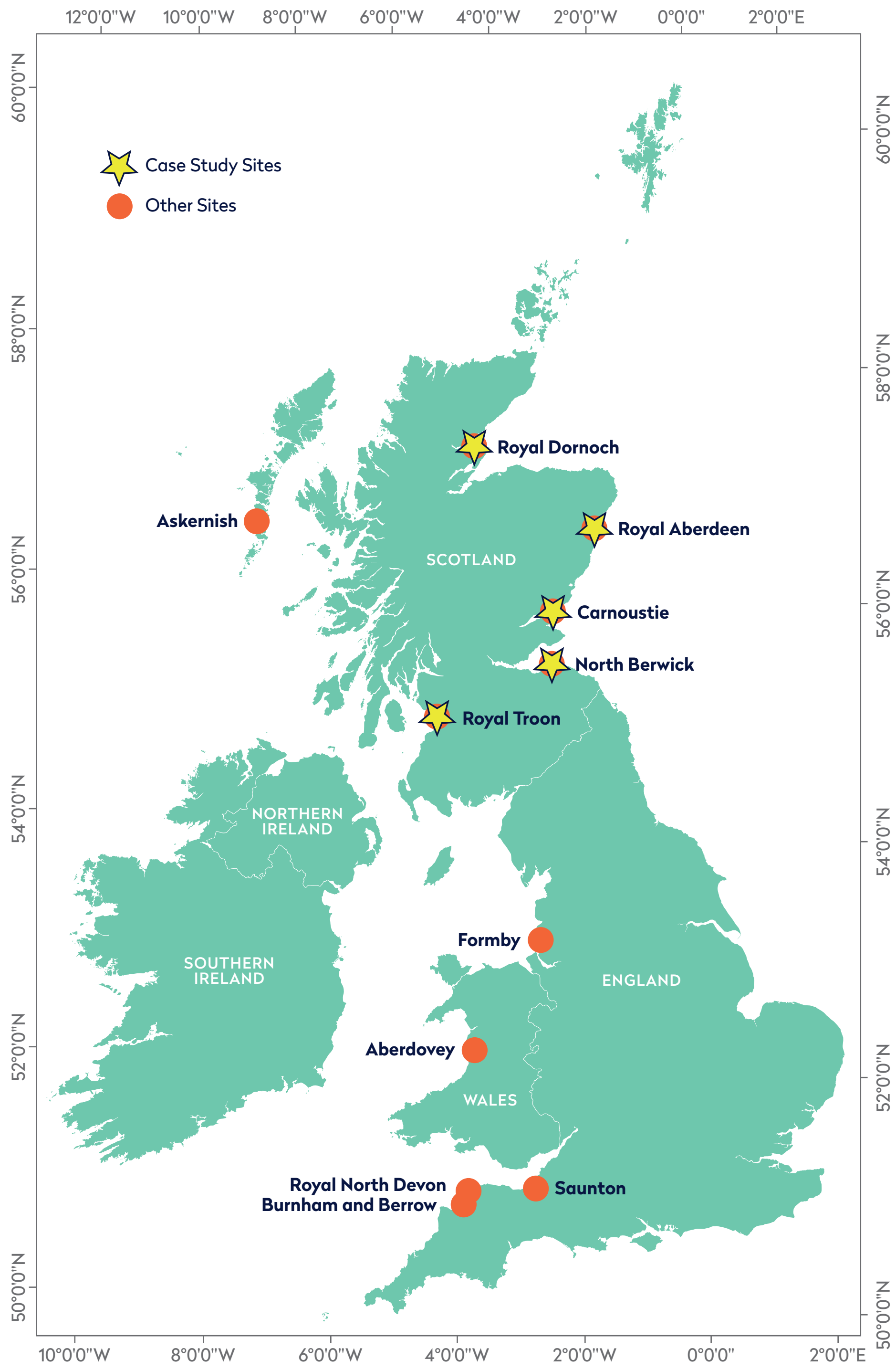

Figure 5. Locations of coastal golf courses where soil samples were collected. Stars highlight the golf course used as case studies for site specific soil organic carbon assessments.

Approach

Soil samples were collected from different soil zones classified as rough, fairways and when permittable, the greens. The soil samples were collected using a 15cm long hand driven soil sampler. In total 436 samples were collected with 198 originating from the rough, 196 from fairways and 42 from greens. The soil samples were returned to the University of St Andrews where they were oven dried at 50°C for 72 hours allowing the dry bulk density to be determined. Next the samples were milled to a fine powder by hand and the organic carbon content of the soil determined using an Elemental Analyser.

To estimate the soil (top 15cm) organic carbon store in coastal golf courses it is necessary to understand the aerial extent of the different golf course zones (rough, fairway, greens). However, there is limited data available and in England and Wales habitat mapping does not include man-made landscapes such as golf courses. In Scotland, the Habitat Map of Scotland (HabMoS) does include golf courses within the data compiled from the sand dune vegetation survey of Scotland (Dargie, 1998), which include most coastal golf courses. These surveys map land cover type but do not directly map golf course features such a rough, fairways or greens. The improved grassland land cover classification can be used as a surrogate for fairways and greens, while the remaining areas within the boundaries of the golf course (excluding hard structures) can be considered rough. This approach allows first order estimates of the area of each golf course zone, but the accuracy of this approach is likely to remain highly variable between golf courses.

Soil samples were collected from different soil zones classified as rough, fairways and when permittable the greens.

The mapped areal extent of the different golf course zones are then combined with the average values from dry bulk density and OC content measurements following the standard calculation steps (Appendix A) to produce first order estimates of the organic carbon held within the top 15cm of soil in the different golf course zones alongside the course as a whole.

In Scotland it is also possible to estimate potential erosion of the coastline and associated potential loss of soil organic carbon in the coming decades due to sea level rise. Using mapping from the Dynamic Coasts project (Rennie et al., 2021) that integrates coastal erosion models (Fitton et al., 2016; Muir et al., 2019) with future sea level projections (Palmer et al., 2018) to estimate the position of the future shoreline, allowing the quantity of land and organic carbon lost to erosion to be estimated. To estimate future organic carbon loss the study takes into consideration the best- and worst-case scenarios based on projected sea level in 2050 and 2100.

The best-case scenario is based upon the **RCP2.5, 50th percentile** emission scenario which expects rapid emissions reductions in the coming years. Even by dramatically reducing global emissions sea level will continue to rise, with 58% of soft shores in Scotland likely to show erosion and on average 11m of beach will potentially be lost to the sea by 2100.

The worst-case is based upon the **RCP8.5, 95th percentile** emission scenario which assumes continued emissions with no reductions. In Scotland, this would result in 72% of our soft shores being eroded by 2100, and on average a loss of 14m of coastline to the sea.

Coastal golf course case studies in Scotland

Due to data availability, case studies highlighting the soil organic carbon storage both today and, in the future, can only be produced for coastal golf course in Scotland, these include:

- **Royal Aberdeen** (Balgownie Course)
- **Royal Dornoch** (Championship)
- **North Berwick** (West Links)
- **Royal Troon** (Old Course)
- **Carnoustie** (Championship)

Royal Aberdeen (Balgownie Course)

The Balgownie golf course at Royal Aberdeen covers an area of 0.95km² (Figure 6A). Habitat mapping estimates that 37% of the course consists of fairways and greens, while the rough makes up 49% of the course. The remaining 14% is made up no vegetated environments or hard structures (Figure 6B).

Figure 6. Balgownie golf course **(A)** golf course extent and sampling location; **(B)** simplified habitat mapping.

A total of 54 surficial (top 15cm) soil samples were collected from the three zones (rough, fairway, green) of the Balgownie course (Figure 6A) allowing the determination of the dry bulk density and organic carbon content of the soils within these zones (Figure 7).

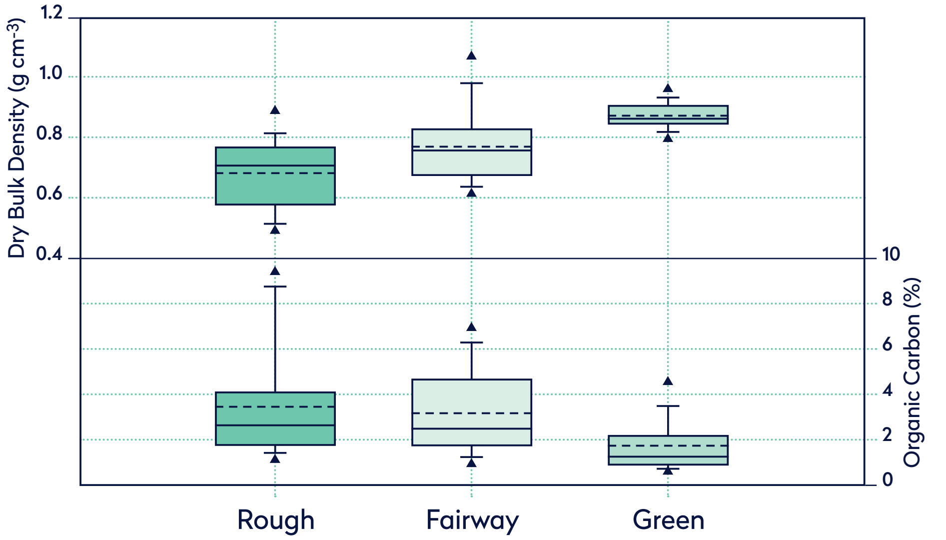

Figure 7. Dry Bulk density and organic carbon content of the three soil zones at the Balgownie golf course. The solid line represents the median value, the dotted line highlights the mean, and the triangles represent the 5th and 95th percentiles.

Across the three zones of the Balgownie golf course the rough and fairways hold 3.2 ± 2.3% organic carbon and 3.0 ± 1.8% organic carbon respectively. In comparison the greens contain significantly less organic carbon with on average 1.5 ± 1.1% organic carbon.

Through the combination of the simplified habitat mapping (Figure 6B) and the soil properties (Figure 7) it is estimated that the top 15cm of soil within the Balgownie golf course holds **2736.7 tonnes of organic carbon (3.3kg C m^{-2})** with the fairways and greens holding 1303.9 tonnes of organic carbon (3.7kg C m^{-2}) and the rough holding 1432.8 tonnes of organic carbon (3.1kg C m^{-2}).

Figure 8. Estimated erosion of the coast at the Balgownie golf course 2100 based upon different emission scenarios **(A)** RCP2.6, 50th percentile and **(B)** RCP8.5, 95th percentile. Data acquired from Dynamic Coasts.

www.dynamiccoast.com

Under the low emission scenario **(RCP2.6, 50%)** it is estimated the Balgownie golf course has the potential to lose **67.1 tonnes of organic carbon** (2.5% of current organic carbon stock) by 2050 and up to **346.4 tonnes of organic carbon** (12.6% of current organic carbon stock) by 2100 (Figure 8A). In the high emission scenario **(RCP8.5, 95%)** it is estimated that **90.3 tonnes of organic carbon** (3.3% of current organic carbon stock) will be lost by 2050 and up to **662.1 tonnes of organic carbon** (24.2% of current organic carbon stock) will be lost by 2100 (Figure 8B).

Royal Dornoch (Championship)

The Royal Dornoch golf course covers an area of 1.32km² (Figure 9A). Habitat mapping estimates that 23% of the course consists of fairways and greens, while the rough makes up 62% of the course. The remaining 15% is made up no vegetated environments or hard structures (Figure 9B).

Figure 9. Royal Dornoch golf course **(A)** golf course extent and sampling location; **(B)** simplified habitat mapping.

A total of 52 surficial (top 15cm) soil samples were collected from the three zones (rough, fairway, green) of the Royal Dornoch course (Figure 9A) allowing the determination of the dry bulk density and organic carbon content of the soils within these zones (Figure 10).

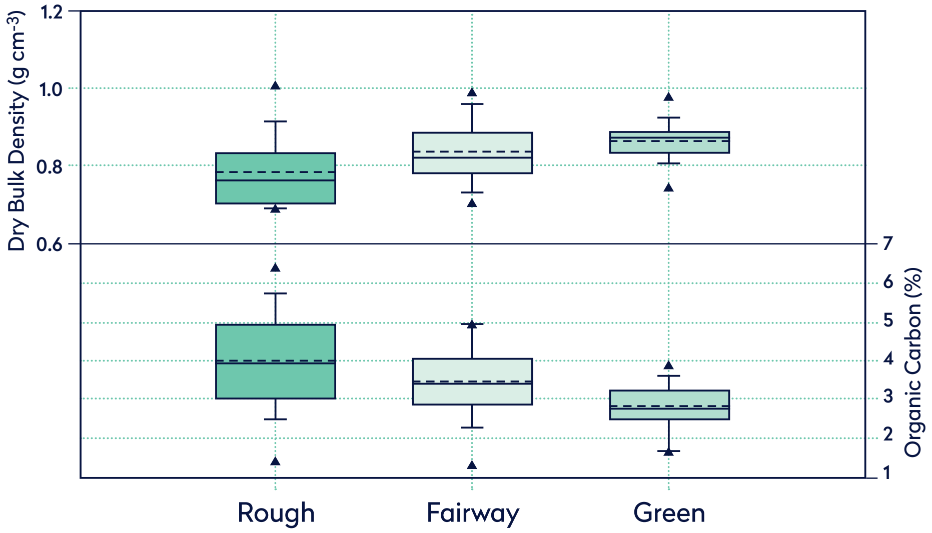

Figure 10. Dry Bulk density and organic carbon content of the three soil zones at the Royal Dornoch golf course. The solid line represents the median value, the dotted line highlights the mean, and the triangles represent the 5th and 95th percentiles.

Across the three zones of the Royal Dornoch golf course the rough and fairways hold 4.0 ± 1.2% organic carbon and 3.5 ± 0.9% organic carbon respectively. In comparison the greens contain significantly less organic carbon with on average 2.8 ± 0.6% organic carbon.

Through the combination of the simplified habitat mapping (Figure 11B) and the soil properties (Figure 10) it is estimated that the top 15cm of soil within the Royal Dornoch golf course holds **5199.6 tonnes of organic carbon (4.6kg C m^{-2})** with the fairways and greens holding 1301.6 tonnes of organic carbon (4.4kg C m^{-2}) and the rough holding 3897.9 tonnes of organic carbon (4.7kg C m^{-2}).

Figure 11. Estimated erosion of the coast at the Royal Dornoch golf course 2100 based upon different emission scenarios **(A)** RCP2.6, 50th percentile and **(B)** RCP8.5, 95th percentile. Data acquired from Dynamic Coasts.

www.dynamiccoast.com

Under the low emission scenario **(RCP2.6, 50%)** it is estimated the Royal Dornoch golf course has the potential to lose **153.4 tonnes of organic carbon** (2.9% of current organic carbon stock) by 2050 and up to **652.8 tonnes of organic carbon** (12.6% of current organic carbon stock) by 2100 (Figure 11A). In the high emission scenario **(RCP8.5, 95%)** it is estimated that **231.7 tonnes of organic carbon** (4.5% of current organic carbon stock) will be lost by 2050 and up to **1130.9 tonnes of organic carbon** (21.8% of current organic carbon stock) will be lost by 2100 (Figure 11B).

North Berwick (West Links)

The North Berwick golf course covers an area of 0.58km² (Figure 12A). Habitat mapping estimates that 56% of the course consists of fairways and greens, while the rough makes up 32% of the course. The remaining 12% is made up no vegetated environments or hard structures (Figure 12B).

Figure 12. North Berwick golf course **(A)** golf course extent and sampling location; **(B)** simplified habitat mapping.

A total of 42 surficial (top 15cm) soil samples were collected from the three zones (rough, fairway, green) of the North Berwick course (Figure 12A) allowing the determination of the dry bulk density and organic carbon content of the soils within these zones (Figure 13).

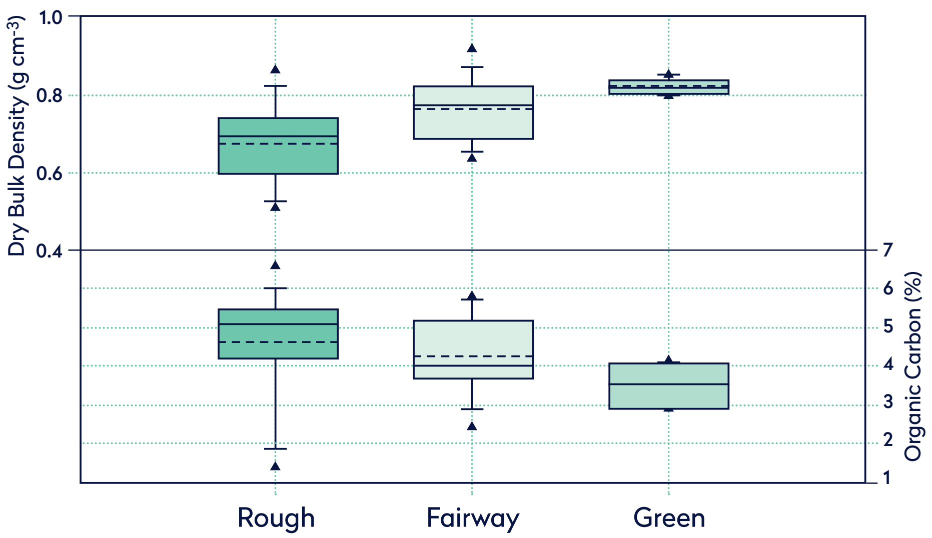

Figure 13. Dry Bulk density and organic carbon content of the three soil zones at the North Berwick golf course. The solid line represents the median value, the dotted line highlights the mean, and the triangles represent the 5th and 95th percentiles.

Across the three zones of the North Berwick golf course the rough and fairways hold 4.6 ± 1.4% organic carbon and 4.2 ± 1.0% organic carbon respectively. In comparison the greens contain significantly less organic carbon with on average 3.5 ± 0.6 % organic carbon.

Through the combination of the simplified habitat mapping (Figure 14B) and the soil properties (Figure 13) it is estimated that the top 15cm of soil within the North Berwick golf course holds **2393.5 tonnes of organic carbon (4.8kg C m^{-2})** with the fairways and greens holding 1527.7 tonnes of organic carbon (4.8kg C m^{-2}) and the rough holding 860.6 tonnes of organic carbon (4.7kg C m^{-2}).

Figure 14. Estimated erosion of the coast at the North Berwick golf course 2100 based upon different emission scenarios **(A)** RCP2.6, 50th percentile and **(B)** RCP8.5, 95th percentile. Data acquired from Dynamic Coasts.

www.dynamiccoast.com

Under the low emission scenario (RCP2.6, 50%) it is estimated the North Berwick golf course has the potential to lose **31.0 tonnes of organic carbon** (1.3% of current organic carbon stock) by 2050 and up to **104.1 tonnes of organic carbon** (4.3% of current organic carbon stock) by 2100 (Figure 14A). In the high emission scenario **(RCP8.5, 95%)** it is estimated that **37.9 tonnes of organic carbon** (1.6% of current organic carbon stock) will be lost by 2050 and up to **224.4 tonnes of organic carbon** (9.4% of current organic carbon stock) will be lost by 2100 (Figure 14B).

Royal Troon (Old Course)

The Old Course at Royal Troon covers an area of 1.37km² (Figure 15A). Habitat mapping estimates that 21% of the course consists of fairways and greens, while the rough makes up 29% of the course. The remaining 50% is made up no vegetated environments or hard structures or not currently mapped (Figure 15B).

Figure 15. Royal Troon **(A)** golf course extent and sampling location; **(B)** simplified habitat mapping.

A total of 36 surficial (top 15cm) soil samples were collected from the two zones (rough, fairway) of the Royal Troon course (Figure 15A) allowing the determination of the dry bulk density and organic carbon content of the soils within these zones (Figure 16).

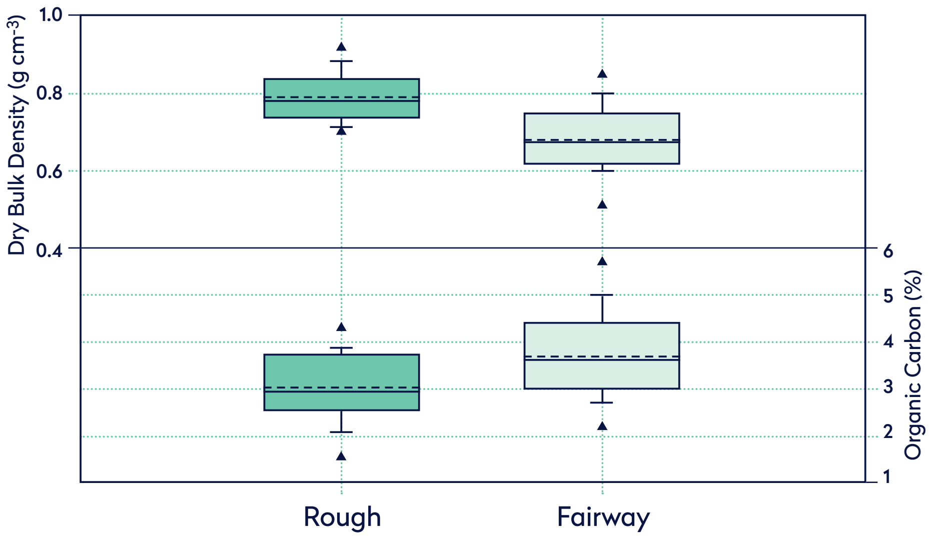

Figure 16. Dry Bulk density and organic carbon content of the three soil zones at the Royal Troon golf course. The solid line represents the median value, the dotted line highlights the mean, and the triangles represent the 5th and 95th percentiles.

Across the three zones of the Royal Troon golf course the rough and fairways hold 3.7 ± 0.9% organic carbon and 3.0 ± 0.7% organic carbon respectively.

Through the combination of the simplified habitat mapping (Figure 17B) and the soil properties (Figure 16) it is estimated that the top 15 cm of soil within the Royal Troon golf course holds **2523.6 tonnes of organic carbon (3.7kg C m^{-2})** with the fairways and greens holding 1021.9 tonnes of organic carbon (3.6kg C m^{-2}) and the rough holding 1501.7 tonnes of organic carbon (3.8kg C m^{-2}).

Figure 17. Estimated erosion of the coast at the Royal Troon golf course 2100 based upon different emission scenarios **(A)** RCP2.6, 50th percentile and **(B)** RCP8.5, 95th percentile. Data acquired from Dynamic Coasts.

www.dynamiccoast.com

Under the low emission scenario **(RCP2.6, 50%)** it is estimated the Royal Troon golf course has the potential to lose **1.9 tonnes of organic carbon** (0.08% of current organic carbon stock) by 2050 and up to **5.1 tonnes of organic carbon** (0.2% of current organic carbon stock) by 2100 (Figure 17A). In the high emission scenario **(RCP8.5, 95%)** it is estimated that **6.3 tonnes of organic carbon** (0.3% of current organic carbon stock) will be lost by 2050 and up to **31.9 tonnes of organic carbon** (1.3% of current organic carbon stock) will be lost by 2100 (Figure 17B).

Carnoustie (Championship)

The Carnoustie golf course covers an area of 1.51km² (Figure 18A). Habitat mapping estimates that 28% of the course consists of fairways and greens, while the rough makes up 65% of the course. The remaining 7% is made up no vegetated environments or hard structures (Figure 18B).

Figure 18. Carnoustie **(A)** golf course extent and sampling location; **(B)** simplified habitat mapping.

A total of 72 surficial (top 15cm) soil samples were collected from the two zones (rough, fairway) of the Carnoustie course (Figure 18A) allowing the determination of the dry bulk density and organic carbon content of the soils within these zones (Figure 19).

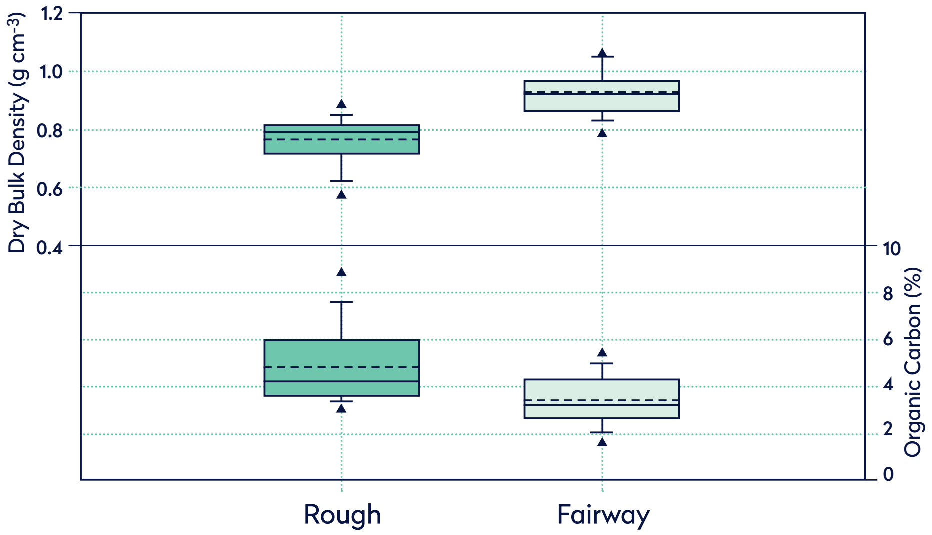

Figure 19. Dry Bulk density and organic carbon content of the three soil zones at the Carnoustie golf course. The solid line represents the median value, the dotted line highlights the mean, and the triangles represent the 5th and 95th percentiles.

Across the three zones of the Carnoustie golf course the rough and fairways hold 2.7 ± 2.3% organic carbon and 2.2 ± 1.6% organic carbon respectively.

Through the combination of the simplified habitat mapping (Figure 20B) and the soil properties (Figure 19) it is estimated that the top 15cm of soil within the Carnoustie golf course holds **7391.9 tonnes of organic carbon** (5.3kg C m^{-2}) with the fairways and greens holding 2003.9 tonnes of organic carbon (4.7kg C m^{-2}) and the rough holding 5388.1 tonnes of organic carbon (5.5kg C m^{-2}).

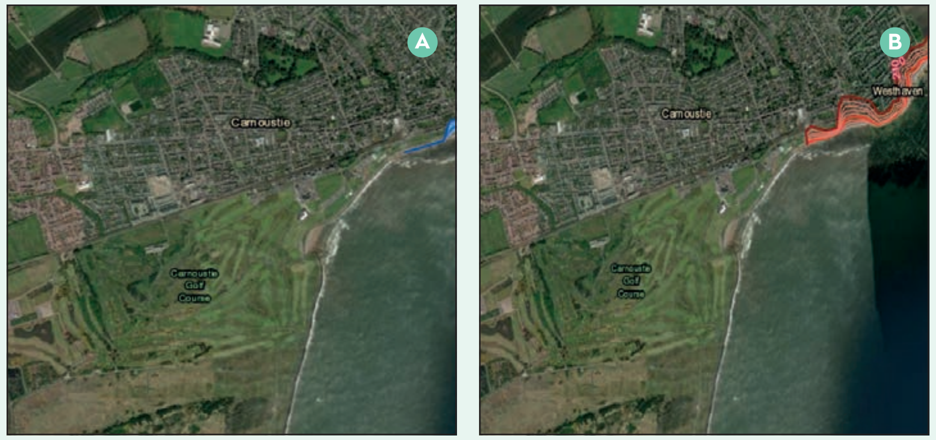

Figure 20. Estimated erosion of the coast at the Carnoustie golf course 2100 based upon different emission scenarios **(A)** RCP2.6, 50th percentile and **(B)** RCP8.5, 95th percentile. Data acquired from Dynamic Coasts.

www.dynamiccoast.com

Under both the low emission (RCP2.6, 50%) and high emission scenarios (RCP8.5, 95%) Carnoustie golf course is predicted to be safe from erosion in both 2050 and 2100 and in-turn will not lose soil organic carbon due to sea level rise.

Summary

Across the five case study sites a similar pattern emerges with the rough and fairways generally containing the greatest quantity of organic carbon.

This pattern is also reflected in the data produced from all 436 soil samples collect from eleven coastal golf courses (Figure 21). The lower organic carbon content measured in the soils related to the greens is likely driven by green-management practices (lowering organic matter for playability).

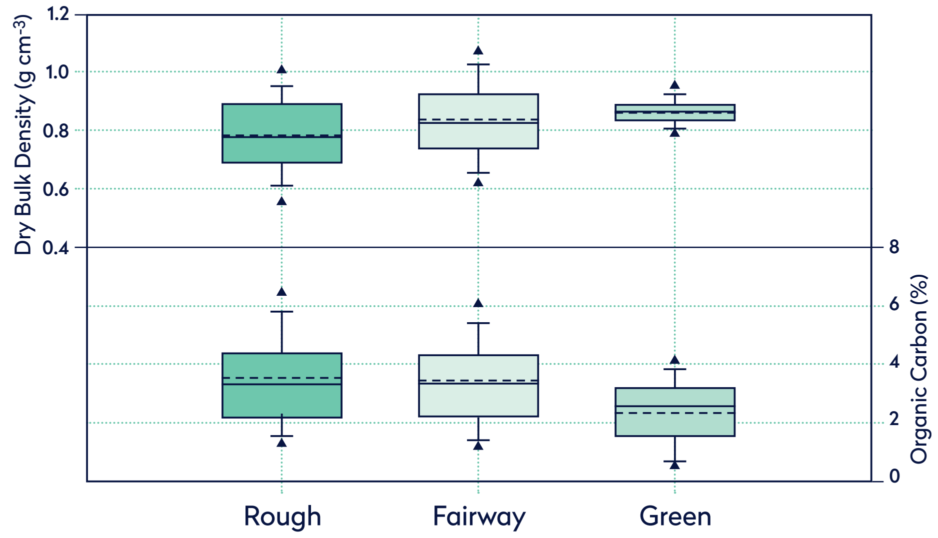

Figure 21. Dry Bulk density and organic carbon content of the three soil zones at all eleven golf courses sampled. The solid line represents the median value, the dashed line highlights the mean, and the triangles represent the 5th and 95th percentiles.

The soil (top 15cm) organic carbon stocks across the five case studies range from 2393.5 to 7391.9 tonnes of organic carbon. Of the different course zones, the rough generally holds the largest quantity of organic carbon followed by the fairways. When normalized for area the golf courses hold between 3.3 and 5.3 kg C m^{-2}. These estimates of OC storage a less than those reported (6.8 ± 1.3 kg C m^{-2}) in the organic carbon stocks estimated for the 435 coastal golf courses in England, Scotland and Wales using the Countryside Survey data (Henrys et al., 2012; *Section 2*) and across all other land cover type (Figure 21). This highlights the potential for the nation-wide estimate of 1.20 to 1.44 million tonnes of organic carbon being held within the top 15cm of soil in coastal golf courses to have been overestimated.

In the coming decades the five case study sites will be subject to significantly different levels of erosion and organic carbon loss due to rising sea level. Carnoustie golf course is unlikely to be impacted under any emission scenario by 2100. At the other end of the spectrum, up to 24.2% of the current soil organic carbon stock at Royal Aberdeen is at risk of loss by 2100. This highlights the need for bespoke soil organic management plans to be developed for individual courses and one size fit all solutions will not be appropriate for effective management planning and decision making.

Recommendations.

Recommendations

- Baseline soil organic matter assessments should be carried out prior to management interventions taking place to ensure that any changes in soil organic carbon can be measured and accounted for in response to these management interventions.
- To accurately quantify the soil organic carbon store within a golf course, sample collection and analysis must be undertaken following a systematic methodology.
- Improved spatial mapping of golf course landscapes (and their management regimes) are essential measures to improve the estimation of soil organic carbon storage across the heterogeneous landscape.
- Bespoke soil organic carbon management plans need to be developed for individual golf courses to achieve optimum climate positive action; such actions must be considered in light of the need to prioritize greenhouse gas emission reductions from golf course landscapes wherever these are possible.
- The golf course soil organic carbon store cannot be managed in isolation from the wider coastal organic carbon store; and the risks of coastal erosion resulting from accelerating sea-level rise should be evaluated as part of all coastal golf course sustainability planning.

To accurately quantify the soil organic carbon store within a golf course, sample collection and analysis must be undertaken following a systematic methodology.

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R&A

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Appendices.

Appendix A – Practical guide to golf course soil sampling and carbon stock assessment used in this study

Sampling

A minimum of 36 soil samples are required from each golf course to produce a representative sample set to allow the calculation of soil organic carbon stocks. The soil samples should be spatially distributed across the course covering as many different land covers as feasible.

For comparison to this study and the wider Countryside Survey (Henrys et al., 2012) the sample should be taken to a depth of 15cm. In this study we used a metal hand driven soil sampler (cylindrical tube with handle).

Sampling procedure

- Assure sampling tool is clean.
- Push sampling tool into the soil to a depth of 15cm. If this is not possible record the depth in which the sampling tool is inserted in the soil.
- Place the soil sample in a sample container (plastic bag or tub) with the sample identification clearly displayed on sample container.
- Record location using a GPS.
- Fill in sample logging sheet with location and sampling information.
- Clean sampling tool for next site.

Sample analysis

It is unlikely that golf facilities will have the ability to undertake the analysis of the soil samples in-house and external laboratory support will be required. To assure that data produced from different golf courses and external laboratories are comparable a standard analytical approach should be used.

Analytical procedure

- Weigh the sample (g)
- Oven dry sample at 50°C for 72 hours.
- Weigh sample (g)
- Mill sample to a fine powder using mortar and pestle or ball mill.
- Place 10-12mg of milled sample is silver capsule.
- Acidify sample using 10% Hydrochloric acid.
- Oven dry sample at 50°C for 24 hours.
- Place sample in Elemental Analyser to measure carbon content with certified analytical standards.

From this data the dry bulk density can be calculated:

Dry bulk density (g cm^{-3}) = Dry soil mass (g) / Wet soil volume (cm^3)

The wet soil volume can be calculated using the dimensions of the sampling tool, for a cylindrical sampling tool:

Wet soil volume (cm^3) = π x radius^2 (cm) x soil depth (cm)

The School of Geography and Sustainable Development at the University of St Andrews can provide external laboratory support for golf courses seeking to generate soil organic carbon stock assessments; please contact: **bluecarbon@st-andrews.ac.uk**

Soil organic carbon stock estimation

Area determination

To calculate accurate soil OC stock estimates the area of the golf course and the different land cover types (in its simplest form this is rough, fairway, green, hard structures) is required. It is likely that golf course managers will have a good understanding of the area coverage of their courses.

If this is not the case the total extent of the golf course can be determined form the **Ordnance Survey Greenspace dataset**. Other datasets such as habitat mapping offer some potential to further break down the golf course into different land covers or zones (rough, fairway, green) these datasets are freely available from national agencies such as NatureScot, Natural England, Natural Resources Wales and Department of Agriculture, Environment and Rural Affairs in Northern Ireland.

A free user-friendly alternative is to use the basic measurement tools in **Google Earth** to determine the total area of the golf course and the different zones.

Organic carbon stock calculations

Once all the data is in place organic carbon stock calculations can be undertaken following the standard steps:

Soil volume (m^2) = Area of course (m^2) x Soil depth (m)

Soil mass (kg) = Soil volume (m^2) x Soil dry bulk density (kg m^{-3})

Note the dry bulk density units are kg m^{-3}, this can be calculated by multiplying g cm^{-3} by 1000.

Soil organic carbon stock (kg) = Soil mass (kg) / 100 x OC content (%)

Soil organic carbon stock (tonnes) = Soil organic carbon stock (kg) / 1000

Soil organic carbon storage (kg C m^{-2}) = Soil organic carbon stock (kg) / area(m^2)

Appendix B provides a simple automated Carbon Calculator to assist in these calculations (available from bluecarbon@st-andrews.ac.uk).

Appendix B – Example of sampling logging sheet

Golf Course	Golf Course ABC
Date	01/01/24
Sampling Tool – dimensions (cm)	Cylinder – diameter – 1cm

Site ID	Description	Hole	GPS coordinates	Soil depth (cm)
1	Fairway	1	51.253604, -3.005412	15

R&A

The R&A group of companies was formed in 2004 to take on The Royal and Ancient Golf Club of St Andrews' responsibilities for governing the Rules of Golf, staging The Open, golf's original championship, and developing the sport. The World Golf Museum in St Andrews is part of The R&A group.

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The R&A has responsibility for running a series of world class amateur events and international matches in women's and girls' as well as men's and boys' golf. The R&A stages the AIG Women's Open and works with the DP World Tour to stage the Senior Open presented by Rolex.

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