Carbon Sequestration in Coastal Soils under Different Land Use in Schleswig-Holstein, Northern Germany

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Abstract

Carbon sequestration was studied in the coastal soils of the "Katinger Watt", a former tidal flat of the North Sea coast in Schleswig-Holstein, Northern Germany. Carbon sequestration was determined by the ecological approach and calculated as the difference between total annual net primary production and total annual heterotrophic respiration. The measurement was conducted every month from June 2006 to May 2007. All sites were underlain by very young soils that developed after the former marine tidal flat was diked in 1973. After diking, the soils were drained and terrestrial soil formation continued for 35 year. The initial conditions after diking were similar in all sites. All soils were classified as *Normkalkmarsch* according to the German soil classification, as *Calcic Fluvisol* (WRB, 2007) and as *Typic Fluvaquent* (USDA, 2010). The annual carbon sequestration in the arable land was estimated as -0.82 t C ha⁻¹ yr⁻¹ which indicates that the arable land acted as a net CO₂ source during the investigation period. In the grassland, about 0.18 t C ha⁻¹ yr⁻¹ was sequestered in the soil. In other words the grassland acted as a carbon sink during the investigation period.

Keywords: Carbon sequestration, Arable land, Grassland, Heterotrophic respiration, Net primary production

1. Introduction

Soils are the largest reservoir of carbon in the terrestrial ecosystem. They contain more than four times the amount available in the biotic pool and about three times more than the amount in the atmospheric pool (Lal, 2004a). The type of land use, soil cultivation techniques (John et al., 2005, Six et al., 2002), and management practice are important factors in controlling organic carbon storage in soils (Smith, 2004; Tan & Lal, 2005). In addition, abiotic factors such as temperature and water contents influence carbon sequestration by affecting soil microbial activity and plant productivity (Jones et al., 2006).

Carbon sequestration is defined as the removal of atmospheric CO_2 by photosynthesis and the storage of fixed carbon in plant biomass and soil organic matter (Lal, 2004b), thereby storing CO_2 in different carbon pools of varying lifetime (Jones & Donnelly, 2004). These carbon pools are comprised of living and dead above and below ground biomass, wood products and soil organic matter.

Carbon sequestration in soils can be investigated directly by measuring changes in carbon pools, and indirectly by using ¹³C as a tracer, or by using simulation modeling (Jones & Donnelly, 2004). In this study, carbon sequestration was determined by direct measurements based on an ecological approach. In this approach the annual net primary production (NPP) and the net ecosystem production (NEP) was determined. Net ecosystem production equals carbon sequestration in the ecosystem which was determined from the difference between net primary production and heterotrophic respiration (R_h) (Jones & Donnelly, 2004; Schulze et al., 2002; Schulze et al., 2000; Verburg et al., 2004).

The impact of land use on carbon sequestration was studied in the coastal Nature Reserve "Katinger Watt", a diked young marshland at the North Sea in Schleswig-Holstein, Northern Germany. The site was a former sea-floor of a tidal flat that was diked 35 years ago when the Eider flood-barrier was built. Since the terrestrial soils in this area have a very short history, homogeneous conditions, and different land uses, the Katinger Watt sites are very suitable for field studies on the impact of land use on carbon sequestration. The main objective in this study was to characterize the effect of land use on carbon sequestration in coastal soils of the Katinger Watt. Two land use types (arable land and grassland) typical for the Katinger Watt were investigated in the presented study.

2. Materials and Methods

Two different land use types on the investigation area in the Katinger Watt were chosen for this investigation. These study sites are arable land and grassland. The arable land sampling site is located at the position 3491163 E, 6018500 N, and the grassland sampling site at the position 3491735 E, 6016357 N.

Soil samples were taken every month between June 2006 and May 2007 at the respective study site. Mixed soil samples were collected from soil depths of 0-5 cm, 5-10 cm and 10-30 cm and stored in plastic bags. Mixed soil samples were sieved through a 2 mm mesh and plant residues and roots were removed. Undisturbed soil samples were collected in 100 ml cylindrical steel cylinders (10 cm diameter) for bulk density. The total soil carbon content was determined by a CNS elemental analyser (Elementar, Vario Max) using milled samples. Soil inorganic carbon was quantified by gas chromatography after treatment with phosphoric acid. The organic carbon content was calculated as the difference between total and inorganic carbon

For measurements of heterotrophic respiration, soil samples were stored in the refrigerator at 4°C and analysed as soon as possible after sampling. Heterotrophic respiration (R_h) was measured by a Sapromat respirometer equipped with 12 measuring channels (VOITH –SULZER, Ravensburg; Germany) at 22°C for 24 h.The temperature response of heterotrophic respiration was measured by incubating soil samples from the arable land and grassland at 9°C, 12°C, 18°C and 25°C in the Sapromat and quantifying CO₂ production. Subsequently the rates for heterotrophic respiration at different temperatures were fitted to the Arrhenius equation.

To identify plant species at the grassland site, a inventory was carried out in June 2007. On four quadrates (one square meter each) plant species were identified, their abundance quantified and the ecological key for vegetation identified.

To determine the plant biomass in the grassland and arable land three quadrates (0.0625 m^2) were randomly selected in each study site. A steel frame (25 x 25 cm) was pushed into the soil to define the sampling area. Above ground biomass in the quadrate was clipped at the soil surface and sampled in plastic bags. All material was sorted in the laboratory. Grass biomass was separated into live leaves and litter (including standing dead). At the arable land, rapeseed was separated into live leaves, stem, seeds and litter (including standing dead) and wheat was separated into live leaves and litter (including standing dead) and wheat was separated into live leaves and litter (including standing dead) and sampled by collecting the soil in the steel frame down to a depth of 30 cm after removing all above ground plant biomass. These samples were washed over a 2 mm sieve to remove the mineral soil and subsequently sorted into coarse roots (> 2 mm) and fine roots (< 2 mm). All plant biomass samples were dried at 70°C for 72 h and then weighed, milled and carbon was determined with an CNS elemental analyser (Elementar, Vario Max) as described above for the soil samples.

Soil temperature was measured at the surface and in depths of 2 cm, 5 cm, 10 cm, 15 cm and 20 cm with a portable temperature probe (SiKA).

3. Results and Discussion

The monthly net primary production was calculated from the changes in plant biomass between each sampling time. The monthly net primary production (NPP) in the arable land is presented in Figure 1. Between June and July 2007 NPP was positive due to a net increase of plant biomass during growth. It became negative in August 2006 due to harvest of rapeseed and stayed negative until the wheat seedlings started to grow significantly. The annual net primary production (NPP) was calculated from the sum of monthly NPP. Total NPP for rapeseed and wheat was 170 g C m⁻² yr⁻¹ and 536 g C m⁻² yr⁻¹, respectively giving the sum of an annual NPP of 706 g C m⁻² yr⁻¹.

In the grassland (Figure 1), the growth season peaked in June 2006 with a maximum NPP of 212 g C m⁻². Due to mowing in July 2006 the above ground NPP was negative resulting in a low total NPP of 18 g C m⁻². The growing season ended in October 2006 indicated by a steep drop of NPP from 91 g C m⁻² to -195 g C m⁻² in November 2006 which was the lowest value measured during the whole investigation period. Between November 2006 and January 2007 the grassland was a net carbon source but in February 2007 NPP became positive again and increased until May 2007. The annual net primary production was calculated from the sum of monthly NPP and was 420 g C m⁻² yr⁻¹. Total above ground NPP was 134 g C m⁻² yr⁻¹ and total below ground NPP 286 g C m⁻² yr⁻¹.

The grassland inventory identified the representative plant species at the grassland site. There was a very high covering range between 86 to 96 %. Plant species in the grassland belonged to grasses, herbs, orchids, mosses and shrubs. The grassland was dominated by herbaceous vegetation such as red clover (*Trifolium pretense*) with 16 %, 11 % of white clover (*Trifolium repens*), 13 % creeping buttercup (*Ranunculus repens*), and 8 % burr medick (*Medicago minima*) and 1 % European yellowrattle (*Rhinanthus alectorolophus*). Grass species were dominated by 10 % of red fescue (*Festuca rubra*), 7 % common velvetgrass (*Holcus lanatus*), 6 % meadow fescue (*Festuca pratensis*) and creeping bentgrass (*Agrostis stolonifera*), respectively. There were orchids such as health spotted-orchid (*Dactylorhiza maculatea*) and marsh Helleborine (*Epipactris palustris*). *Dactylorhiza maculatea* by water. The vegetation species showed that the site were calcareous, alkaline and wet. High soil moisture and pH (7-8) was indicated by species such as common reed (*Phragmites australis*), health spotted-orchid (*Dactylorhiza maculate*), longbract sedge (*Carex extensa*), distant sedge (*Carex distans*), and marsh Helleborine (*Epipactris palustris australis*), health spotted-orchid (*Dactylorhiza maculate*).

3.1 Heterotrophic respiration under arable land and grassland

Heterotrophic respiration rates (R_h) were measured between June 2006 and May 2007 in the uppermost 30 cm of the arable land soil. Since soil temperature varied considerably during the investigation period but heterotrophic respiration was measured routinely at 22°C in the laboratory the temperature response of heterotrophic respiration in the arable land was measured and the obtained data fitted to the Arrhenius equation. To calculate the rates of heterotrophic respiration at the respective *in situ* soil temperature (see Figure 3) the rates measured at 22°C in the laboratory were corrected with the fitted Arrhenius equation. The calculated activation energy (Ea) of heterotrophic respiration was 35 kJ/mol (Figure 2).

The heterotrophic respiration (R_h) rates were generally lower in the winter season and increased in summer (Figure 3). However, highest rates were measured in September 2006 (132 mg CO₂ – C m⁻² h⁻¹) after rapeseed was harvested and the soil was ploughed. Minimum values were measured in October 2006 with 33 mg CO₂ m⁻² h⁻¹.

Between June 2006 and May 2007, 788 g C m⁻² were mineralized by heterotrophic respiration. The soil water content varied between 11 and 25 % and the soil temperature between 6 and 22°C in the uppermost 5 cm of the soil (Figure 3).

As in the arable land, the temperature response of heterotrophic respiration rates (R_h) were measured at 22°C and the results were corrected to the respective *in situ* temperature (Figure 2). The calculated activation energy (Ea) of heterotrophic respiration was 294 kJ/mol.

Heterotrophic respiration (R_h) was highest in summer and decreased in winter (Figure 3) R_h peaked with 126 mg CO₂ - C m⁻² h⁻¹ in September 2006 and decreased throughout autumn. The minimum values were measured in January 2007 (2 mg CO₂ - C m⁻² h⁻¹) when the temperature was lowest.

Total annual heterotrophic respiration, i.e. organic matter mineralization, was 402 g C m^{-2} . Soil temperature varied between 5 and 24°C and soil water content varied between 6 and 59 %.

Heterotrophic respiration rate decreased with soil depth in the grassland but not in the arable land due to tillage. This was also reported in recent studies (Dilly et al., 2005; Kaiser & Heinemeyer, 1993). The seasonal pattern of heterotrophic respiration was similar in all different land uses. The heterotrophic respiration rate was highest in the growing period and lowest in the winter season. Similar result were found by Kaiser and Heinemeyer (1993) and Dilly (2003). Soil temperature was an important factor controlling the monthly changes in heterotrophic respiration within the investigation sites. Several previous studies have shown that soil temperature is an important factor controlling soil respiration (Buchmann, 2000; Janssens et al., 2001; Yazaki et al., 2004). Total annual heterotrophic respiration rates in the uppermost 30 cm were significantly different depending on the type of land use. Total annual heterotrophic respiration was highest in the arable land (7.88 t C ha⁻¹yr⁻¹).

3.2 Carbon sequestration under arable land and grassland

Carbon sequestration equals the net ecosystem production and was calculated as the difference between NPP and heterotrophic respiration. The seasonal change in the carbon sequestration is presented in Figure 4. The carbon sequestration clearly increased in the growing season and decreased in the autumn and winter season.

In arable land carbon sequestration was positive (CO₂ uptake by plant) in June and July 2006 and became negative (net release of CO₂ to the atmosphere) between August 2006 (-295 g C m⁻²) and February 2007 when the rapeseeds were harvested and growth of the seeded wheat was small. With beginning of the growing season in March 2007 carbon sequestration became positive reaching maximum values of 272 g C m⁻² in May 2007. The annual carbon sequestration was estimated as -82 g C m⁻² which indicates that the arable land acted as a net CO₂ source during the investigation period.

In the grassland (Figure 4), Carbon sequestration was highest in June 2006 (107 g C m⁻²) and became negative in July (-78 g C m⁻²) and August 2006 (-39 g C m⁻²) which was due to mowing and harvest of the grass. In September and October 2006 a net carbon sequestration was measured while a net carbon release was observed between November 2006 (-200 g C m⁻²) and January 2007. Annual carbon sequestration was 18 g C m⁻². In other words the grassland acted as a C sink during the investigation period.

Carbon sequestration in this study decreased in the order: grassland > arable land and ranged between -82 and +18 g C m⁻²yr⁻¹. Similar result were reported by several recent studies which demonstrated that carbon sequestration was highest in grassland, followed by arable land with only the arable land being a net carbon source (Janssens et al., 2005; Liski et al., 2002; Sleutel et al., 2003; Vleeshouwers & Verhagen, 2002). Carbon sequestration was quantified in two *Spartina* marshes by Middelburg et al. (1997). They measured an annual carbon burial of 96-105 g C m⁻²yr⁻¹.

Estimates on carbon sequestration in the arable land have the largest uncertainties among all land use systems (Janssens et al., 2003; Smith, 2004). In arable land, carbon losses are caused by harvest, reducing the amount of carbon being released into the soil, and agricultural practices such as tillage, ploughing, drainage etc. (Janssens et al., 2005). Furthermore land use changes such as conversion of pasture to cropland, and increasing temperatures result in an increasing release of CO_2 from arable land (Sleutel et al., 2006). Additionally, various crop types will lead to large differences in the carbon sequestration even in a scale of small fields (Anthoni et al., 2004).

During the investigation period the grassland acted as carbon sink with a strength of 0.18 t C ha⁻¹yr⁻¹. One reason for the relatively small carbon sequestration was the removal of a considerable part of the above ground biomass by mowing for producing hay and sheep grazing. The frequency and intensity of disturbance plays an important role in the carbon sequestration in grasslands (Soussana et al., 2007). Via hay or silage production, a large amount of the primary production is exported from the plot as hay and silage. The largest part of the organic carbon ingested during grazing is digestible (up to 75 % for highly digestible forages) and hence is respired shortly after intake. A negative carbon sequestration rate was reported by Yazaki et al. (2004) for a Miscanthus sinensis grassland in Japan with a net carbon release of -0.56 to -1.0 t C ha⁻¹yr⁻¹. However, using a similar approach as the present study, Kleber (1997) reported carbon sequestration in fertilized grassland ranging between -0.1 to 5.6 t C ha⁻¹yr⁻¹ and carbon sequestration under grassland was quantified in Australia, UK, New Zealand, Canada, Brazil and the United States between 0.11 to 3.0 t C ha⁻¹yr⁻¹ with a mean of 0.54 t C ha⁻¹yr⁻¹(Conant et al., 2001). However, previous estimates on carbon sequestration in the same grassland as we studied, Dilly et al. (2005) are with 0.90 t C ha⁻¹yr⁻¹ considerably higher than the values that we found. However in latter study carbon sequestration was estimated solely from grassland carbon pools assuming that 100% of the organic carbon was accumulated in the 34 years after diked. The present study however demonstrates, that Dilly et al. (2005) used a sampling site with an over-average carbon content, resulting in an overestimation of the total organic carbon pool in the grassland, resulting in the calculation of a carbon sequestration rate which is too high. Furthermore, the carbon sequestration rates seem to be not linear over the last 30 years but decreased after considerable amounts of organic carbon has been accumulated. It is assumed that the relatively low carbon sequestration rates determined in the current study give a more realistic assumption on carbon fluxes under current situation than the calculations of Dilly et al. (2005).

4. Conclusion

Carbon sequestration was determined by the ecological approach and calculated as the balance between total annual NPP and total annual heterotrophic respiration. The annual carbon sequestration in the arable land was estimated as -0.82 t C ha⁻¹ yr⁻¹ which indicates that the arable land acted as a net CO₂ source during the investigation period. In the grassland, about 0.18 t C ha⁻¹yr⁻¹ was sequestered in the soil. In other words the grassland acted as a C sink during the investigation period.

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Figure 1. Monthly NPP from June 2006 to May 2007. Left is under arable land. Rapeseed grew between June 2006 and August 2006. In September 2007, wheat was seeded that started to grow in October 2007. Right is grassland

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Figure 2. Temperature response of heterotrophic respiration in the arable land. Heterotrophic respiration rates were fitted to the Arrhenius equation. Error bars represent standard deviation for n=3.Right is temperature response of heterotrophic respiration in the grassland

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Figure 3. Monthly heterotrophic respiration rates in the uppermost 30 cm of the arable land (columns) that were corrected to the respective *in situ* temperature. Soil temperature at 5 cm depth (circle) and soil water content in the uppermost 5 cm (square). Error bars represent standard deviations for n = 3. Left is arable land and right is grassland



Figure 4. Monthly carbon sequestration between June 2006 and May 2007. Positive values represent CO_2 uptake by plant (carbon sink) and negative values represent a net CO_2 release by plant to atmosphere (carbon source). Left is arable land and right is grassland