Influence of perennial colonies of piscivorous birds on soil nutrient contents in a temperate humid climate

Henrik Breuning-Madsen, Camilla Ehlers-Koch, Jens Gregersen & Christina Lund Løjtnant

Abstract

During the last decades, the number of perennial colonies of piscivorous birds especially cormorant colonies in North-western Europe has grown rapidly due to protection. Their impact on vegetation has been recognized, as many trees containing perennial colonies of piscivorous birds have collapsed, but the bird's influence on the soil conditions has only in few cases been studied in detail. In this study the influence of perennial colonies of piscivorous birds on soil nutrient contents and accumulation of carbon, nitrogen and phosphorus in a humid climate has been determined by measuring pH, electric conductivity and content of carbon, nitrogen, phosphorus, calcium and potassium in a reference area and in two cormorant sub-colonies. In general, the soils exposed to cormorant guano had lower pH and higher contents of plant available phosphorus, calcium and potassium compared to the control reference soil, especially in the top horizons, and the magnitude of increase in nutrient content varied with the bird-dropping density and the age of the colony. In addition, soil influenced by cormorants had a higher electric conductivity compared to the control reference and can be classified as saline soils. Under influence of the cormorants the herb vegetation below the nesting areas has been changed.

Key words

Cormorants, humid soil, nutrients, electric conductivity.

Henrik Breuning-Madsen (Corresponding author)
Camilla Ehlers-Koch
Department of Geography and Geology, University of Copenhagen, Denmark
E-mail: hbm@geo.ku.dk

Jens Gregersen
Naturreservat Vorsø, Søvind, Denmark

Christina Lund Løjtnant
Department of Biology, University of Copenhagen, Denmark

Geografisk Tidsskrift
Danish Journal of Geography 110(1):25-35, 2010

Introduction

In humid areas, nutrients are leached from the fields to the rivers or ground waters and transported to the sea. The reverse transport of nutrients from the sea to land is less recognized, but in some places it plays an important role. One of the transport agents of nutrients from the marine to the terrestrial environment is the sea birds that breed in the coastal zone. Their diets consist of fish, and they excrete nutrient-rich guano high in N and P (Hutchinson, 1950). The excrements are mainly dropped in the nesting area, and hereby the soils are enriched by nutrients. This process is well known all over the world from penguin rookeries in the Antarctic (Speir & Cowling, 1984), over arid and semi-arid areas (Anderson & Polis, 1999; Wait et al., 2005) to humid temperate areas (Hogg & Morton, 1983; Mun, 1997; Ligeza & Smal, 2003). In arid areas, thick guano layers might develop because of no or little leaching, while in humid areas the precipitation surplus will leach a great part of the nutrients transported from the sea by the birds, and thick guano layers do not develop.

The high input of nutrients from the birds (up to 12,500 nests in a single colony) changes the plant community below the nests significantly, and the soils below have an extraordinary high amount of organic carbon, nitrogen, phosphorus and exchangeable cations (Mun, 1997; Anderson & Polis, 1999; Ligeza & Smal, 2003; Wait et al., 2005). Furthermore, the soils often show higher salinity and lower pH-values below bird colonies than the soils outside the colonies (Sobey & Kenworthy, 1979; Hogg & Morton, 1983;

Mun, 1997; Wait et al., 2005). Soils formed in that way can be named ornithogenic soils, and the World Reference Base (IUSS Working Group WRB, 2006) uses ornithogenic as a diagnostic material to describe this type of soil.

In Denmark, cormorants live near shallow bays and fjords and breed in colonies on land, most commonly in trees close to the shoreline. They build the nests of seaweed, twigs and grasses, and they incubate eggs for c. 24 days. They live on fish like eelpouts *Zoarces viviparus*, dabs *Limanda limanda*, cods *Gadus callarias* and herrings *Clupea harengus*, and, as the main diet is fish, this has led to a conflict with local fishermen, also well known from other parts of the world (Ishida, 1997). For this reason and because of their effect on the trees where they breed, the cormorant was exterminated in Denmark in the late 19th century. The species resettled as a breeder in Denmark in 1938 and has bred in the country since then (Bregnballe & Gregersen, 1995). The protection of the species in Europe increased during the 1970s, and consequently the population has increased markedly in many European countries and in Denmark from about 300 nests in 1971 to about 42,000 nests today (Bregnballe et al., 2003).

In order to study the effect of cormorant colonies on the soil chemical properties and the plant community in a humid temperate area, a detailed soil and plant community survey has been carried out on the island of Vorsø in Horsens Fjord in Denmark, Figure 1. The island hosts the oldest cormorant colony in the country, and during the last decades biologists have registered the number of nests in every tree in selected parts of the forests on the island. As a result, valuable data material is available and can be used in the discussion of the impact of bird colonies on the nutrient level in the soil. Thus, in this paper the impact of the continental sub-species of the great cormorant *Phalacrocorax carbo sinensis* on soil nutrient status of humid soils and plant communities is explored by comparing the nutrient content in the soil at a 24-year-old nesting place with many nests and a high density of bird droppings with a 12-year-old nesting place with fewer nests and a lower density of bird droppings and a nearby control area with no nests and consequently almost no bird droppings.

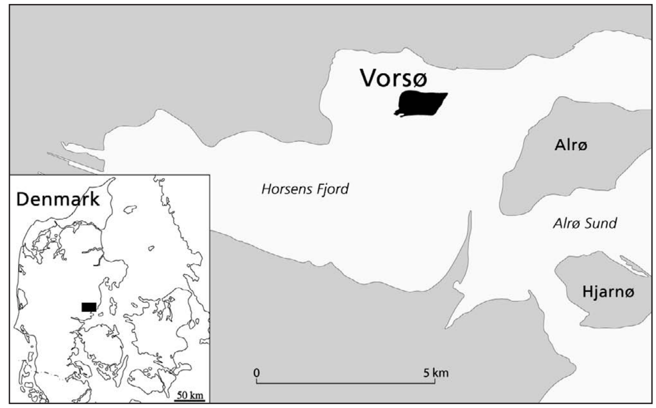

Figure 1: *Map showing the location of Vorsø in Horsens Fjord.*

Investigation area

Vorsø is located in Horsens Fjord in Eastern Jutland, Denmark (55°52' N, 10°00' E) (Figure 1). The area is about 60 ha and includes two small forests. The mean annual precipitation is about 820 mm (Frich et al., 1997), and the mean monthly temperature is between 0.3°C and 16.2°C (Laursen et al., 1999). During summertime, the evapotranspiration exceeds the precipitation in the months from May to August, and the soils dry out. In the other months, the opposite situation exists, and from October/November to April leaching occurs. In total, about 400 mm of the precipitation percolate to the groundwater and leach the soils. The parent material is a lime containing sandy loamy Weichsel till deposited about 18,000 years ago (Houmark-Nielsen, 1987). Since then, the lime has been leached from the uppermost one to two metres of the soil. The topography is rather flat, with the highest point being 4 metres above sea level. A few poorly drained depressions exist in the landscape.

Before 1928, most of the island was farmed, but in 1928 most of the island became a natural reserve, and only 15 ha were kept as farmland. In 1978, the last 15 ha of farmland were included in the natural reserve, and farming was abandoned. Biologists were employed to study and register the development in flora and fauna, and these studies included a registration of how many cormorant nests were used and where they were located (Halberg, 1996).

The cormorants bred on Vorsø until 1864, at which time the cormorants were almost extinct in Denmark. In 1944, they returned to the island (Halberg, 1996), but the number of birds was kept at a low level by shooting, because their main diet conflicted with the interests of the local fishermen. From 1971 the shooting of cormorants at Vorsø stopped, and from 1980 the cormorants in Denmark were totally protected by a conservation act (Bregnballe & Gregersen, 1995). This led to a dramatic increase in the number of cormorants in the country, and on Vorsø

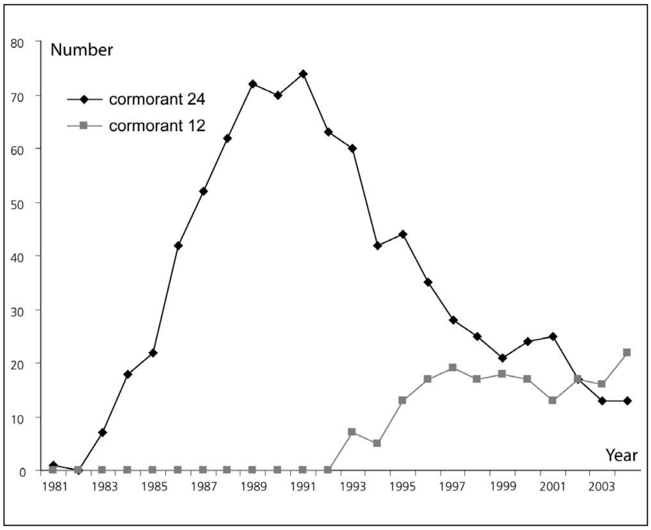

Figure 2: *The number of cormorant nests at cormorant$_{24}$ and cormorant$_{12}$.*

the number of nests increased from about 250 in 1970 to about 5,000 in 1991 (Bregnballe & Gregersen, 1995). The number of nests on Vorsø has declined since 1996, reaching 1,730 nests in 2006.

Three study sites were chosen, cormorant$_{24}$, cormorant$_{12}$ and a control site. Cormorant$_{24}$ is located below a big oak tree (*Quercus robur*) that has hosted cormorant nests for 24 years, and cormorant$_{12}$ is located in Østerskov in a small area with ash trees (*Fraxinus*) that have hosted cormorant nests for 12 years. The control is located in a part of the forest without cormorant nests for at least 100 years, and the forest is dominated by elm (*Ulmus glabra*), oak (*Quercus robur*) and ash (*Fraxinus*).

Figure 2 shows the number of cormorant nests from 1981 to 2005 at the localities cormorant$_{24}$ and cormorant$_{12}$, and both localities are still used for nesting. The location cormorant$_{24}$ is stronger influenced by the cormorants than cormorant$_{12}$, although the dropping area at cormorant$_{24}$ is estimated to be twice as big as that at cormorant$_{12}$. At cormorant$_{24}$, the influence of bird droppings has lasted twice as long as at cormorant$_{12}$, and the average density of nests has been higher during the 24 years at cormorant$_{24}$ than the average density of nests during the 12 years at cormorant$_{12}$. Although the nest density at cormorant$_{12}$ has been higher during the last eight years of study compared to cormorant$_{24}$, because the cormorants have destroyed their nesting possibility at cormorant$_{24}$ by killing the oak, the density of guano deposited at cormorant$_{24}$ in that period has been higher. This because cormorant$_{24}$ has served as a landing and resting tree for the colony in all the years, and from March to November often more than 150 birds have been observed sitting in the tree.

Methods

Soil and plant sampling

At the three sites profiles were excavated for studying the soil profile development.

At each of the three sites, samples were collected from five small excavated pits to the depth of 40 cm and subsequently by boring. At all sites, the mull layer was about 35 to 50 cm's deep, and the samples were taken at 4 fixed depths, i.e. A1: 0-5 cm, A2: 5-10 cm, A3: 25-30 cm and B: 70-80 cm, where A is the mull layer and B the subsoil. This gives five replicates at four depths at all three sites. Composite samples were created by merging an equal amount of soil from the five subsamples or in a few cases the five samples were analyzed separately and mean values were calculated.

Plant material was collected in October 2004 and 2006 at the three sites for determination of species present in the autumn. The Raunkiær-circle method was used (Raunkiær, 1910). A ring with a diameter of 17.8 cm was randomly thrown ten times into the vegetation, and all species within the circle were determined using the manual of Hansen (1996).

Laboratory analyses

The soil samples were air-dried and passed through a 2 mm sieve. All analyses were made on the soil samples finer than 2 mm, and for all parameters except electric conductivity double or triple determinations were carried out.

The texture was determined by use of the hydrometer method for silt and clay fraction and sieving of the sand fraction (Day, 1965). Total carbon content was determined by dry combustion at 1,350°C using an Eltra CS500-analyzer (Nelson & Sommers, 1996). Total nitrogen was determined by dry combustion at 950°C using a Leco CHN-600 Elemental Analyzer (Bremner, 1996). The plant available content of calcium and potassium was determined by extraction with 1M ammoniumacetate, and the contents were determined by AAS. Total P (P_{Total}) was determined by extracting a soil sample heated to 550°C for 1 hour with 6 M H_2SO_4 for 1 hour, and plant available P (P_{Olsen}) was determined by the bicarbonate method (Olsen & Sommers, 1982). After extraction the phosphorus content was determined spectrophotometrically by the molybdenum-blue

Table 1: *Texture, bulk density and pH (H_2O) for the three sites.*

	Depth cm	Clay <2 mm	Silt 2-63 mm	Sand >63 mm	Bulk density Kg/m³	pH (H_2O)
Cormorant$_{24}$	A1 0-5	-	-	-	400	4.4
	A2 5-10	10	27	63	1,200	3.8
	A3 25-30	10	27	63	1,200	3.6
	B 70-80	7	20	73	1,700	4.6
Cormorant$_{12}$	A1 0-5	7	22	71	1,000	4.6
	A2 5-10	7	20	73	1,100	3.9
	A3 25-30	8	20	72	1,300	4.4
	B 70-80	7	22	71	1,700	6.8
Control	A1 0-5				900	5.1
	A2 5-10	9	40	51	1,000	4.9
	A3 25-30	12	34	54	1,300	4.9
	B 70-80	7	15	78	1,700	6.5

method (van Reeuwijk, 1995). Soil pH was determined potentiometrically in a suspension of soil and distilled water at a soil-liquid ratio of 1:2.5 (Thomas, 1996). Electric conductivity was determined using the pasta method (Rhoades, 1996). The soil samples were saturated with distilled water for about one week. The water was extracted, and the electric conductivity measured using a Metrohm 712 conductometer.

Results and discussion

Soil horizons, texture, bulk density and pH

At all three sites, the soils have a 35-50 cm thick A horizon that is brownish black (7.5 YR 3/3) to dark brown (7.5 YR 3/2). This horizon superimposes a dull yellowish brown (10 YR 4/3) subsoil with reddish brown mottles. The uppermost 5 cm of cormorant$_{24}$ are strongly influenced by the bird droppings and fallen nest material and form an almost peaty, structureless soil horizon. Pedologically, the control profile shows a weak clay illuviation with a 10 cm thin Bt horizon between 60 and 70 cm depths. At the two other sites, no clay illuviation and formation of a Bt horizon are recognized. The drainage conditions vary from poorly drained soils in the depressions to well drained soils at the higher positions in the landscape. The three profiles studied are rather well-drained although perched water table might develop during wintertime in the subsoil. This causes the formation of pseudogley which can be recognized as mottling in the subsoil. According to Soil Survey Staff (1998), the soils are Inceptisols.

Table 1 shows the texture of the soil samples taken at the three sites. The soil textures are rather uniform, almost all falling into loamy sand according to Soil Survey Staff (1998). The bulk density at the three sites was determined in the main horizons as an average value of three samples of 100 cm^3. The bulk density is low in the top soil, especially at Cormorant$_{24}$. In the three A-horizons, the bulk density stays at a moderate level, but increases significantly at all three sites in the B horizon, to 1,700 kg/m^3.

At the control site, the pH in the soil is rather close to the normal pH profiles for forest areas in Eastern Jutland (Madsen & Munk, 1987). The soil is leached in the topsoil to a pH about 5.0, but in the subsoil the pH is increasing and is close to neutral at the depth of 70-80 cm. The topsoil has a little higher pH than the soil horizon below, probably due to the ion pumping effect of the plant cover that extracts nutrients from the entire soil profile and delivers it back as a litter layer at the surface where it mineralizes. At the cormorant sites, the pH in the A-horizons is much lower than the pH in the control. This is due to the bird droppings that acidify the soil by uric acids. This is especially the case for cormorant$_{24}$ that has extremely low pH values in the lower part of the A-horizons. The effect of the bird

Table 2: *Percent total carbon, nitrogen and phosphorus at the sites cormorant$_{24}$, cormorant$_{12}$ and control.*

Depth cm	Cormorant$_{24}$	Cormorant$_{12}$	Control
Carbon			
A1 0-5	10.0	3.7	3.9
A2 5-10	4.9	2.7	3.0
A3 25-30	2.8	2.3	2.4
B 70-80	0.7	0.2	0.4
Nitrogen			
A1 0-5	1.3	0.4	0.3
A2 5-10	0.5	0.3	0.2
A3 25-30	0.2	0.2	0.2
B 70-80	0.06	0.03	0.02
Phosphorus			
A1 0-5	4.79	0.43	0.06
A2 5-10	0.30	0.17	0.05
A3 25-30	0.37	0.15	0.04
B 70-80	0.13	0.05	0.02

Table 3: *The amount of total carbon, nitrogen and phosphorus (Kg/m^2) to the depth of 50 cm and 100 cm at the sites cormorant$_{24}$, cormorant$_{12}$ and control.*

Depth cm	C Kg/m^2	N Kg/m^2	P Kg/m^2
0-50 cm			
Cormorant$_{24}$	20.9	1.9	2.8
Cormorant$_{12}$	15.3	1.5	1.1
Control	15.6	1.2	0.3
0-100 cm			
Cormorant$_{24}$	26.9	2.4	3.9
Cormorant$_{12}$	17.0	1.7	1.5
Control	19.0	1.4	0.4

dropping acidification is also clear in the B-horizon for cormorant$_{24}$, but at cormorant$_{12}$ the acidification is only in the A-horizon. This clearly demonstrates the effect of the density and time of nesting on the contamination of the soil. The low pH-values at the cormorant sites do not reflect a low nutrient status as would be common, because the bird droppings also contain substantial amounts of, for example, nitrogen, phosphorus, potassium and calcium (Hutchinson, 1950).

Total organic carbon, nitrogen and phosphorus

The total carbon, nitrogen and phosphorus contents are shown in Table 2. The total carbon content in the three uppermost sampling depths is rather high compared to the carbon content in Danish plough layers that have an average carbon content slightly below 2.0% based on about 36,000 soil samples from the Danish soil classification (Madsen & Platou, 1983).

The carbon content decreases with increasing depths as normally found in soils except podzols. Cormorant$_{24}$ has significantly higher carbon content at all depths than the other two sites, while cormorant$_{12}$ and the control have almost the same carbon content. If we consider the four samples to cover the following depths of 0-5 cm, 5-20 cm, 20-50 cm, and 50-100 cm, it is possible to calculate how many kg of carbon the soils contain per square metre to the depth of half a metre and one metre by using the carbon contents in Table 2 and the bulk densities in Table 1.

Table 3 shows that within the uppermost half metre of the soil cormorant$_{24}$ contains 20.9 kg/m^2 of carbon, cormorant$_{12}$ contains 15.3 kg/m^2 and the control 15.6 kg/m^2. This shows that only a dense population of cormorants over a long period of time seems to be able to raise the carbon content in the soil significantly, and cormorant$_{24}$ has about 30% more carbon in the uppermost metre of the profile compared to the control and cormorant$_{12}$. Thus, a low and short-time cormorant influence does not change the carbon content significantly, and it stays at the same level as ordinary forest and agricultural soils.

Within the uppermost metre of the soil cormorant$_{24}$ contains 26.9 kg/m^2 of carbon, cormorant$_{12}$ contains 17.0 kg/m^2 of carbon and the control 19.0 kg/m^2 of carbon. Krogh et al. (2003) showed that the total carbon content in the uppermost metre of the soils for forests and agricultural lands were about 15 kg/m^3, slightly higher in forests compared to farmland. The carbon content in cormorant$_{12}$ and control is slightly above the average, while cormorant$_{24}$ has more than 50% carbon compared to the average in Danish forest and agricultural soils.

Like total carbon content, the nitrogen content is extremely high in the uppermost 5 cm of cormorant$_{24}$. In general, cormorant$_{24}$ shows higher nitrogen contents than cormorant$_{12}$ that shows higher nitrogen contents than the control. In normal soils, inorganic nitrogen accounts for less than 1% of total nitrogen in the A horizons, but for ornithogenic soils inorganic nitrogen accounts for about 10% of the nitrogen content (Ligeza & Small, 2003). This is probably due to the uric acid in the bird droppings. Especially in the top layer, cormorant$_{24}$ is rich in nitrogen. To the depth of one metre, cormorant$_{24}$ contains 2.4 kg of nitrogen per m^2, cormorant$_{12}$ 1.7 kg of nitrogen per m^2 and the control 1.4 kg of nitrogen per m^2. This difference between the three sites is probably due to the high input of nitrogen from the bird droppings. The high nest density and the long period of contamination with bird droppings compared to cormorant$_{12}$ makes cormorant$_{24}$ outstanding compared to the two other sites, cormorant$_{24}$ having about double the content of nitrogen to the depth of one metre compared to the control.

Hutchinson (1950) found that cormorant droppings contain more than 10% nitrogen. This means that the C/N ratio of the droppings must be rather low, and, at two islands influenced by sea bird guano in the Gulf of California, Wait et al. (2005) found that the C/N was slighly lower than 4. Thus, it must be expected that severe contamination of the soil organic matter with cormorant droppings must lead to a decrease in the soil C/N. Table 4 shows the C/N ratio for the three sites. The C/N value in the natural soil, the control, varies between 13 and 15, which are normal values for Danish mulls. At the two cormorant sites, the C/N value is lower (8-10) than that found at the control in the uppermost 10 to 20 cm of the soil, but not as low as that found by Wait at al. (2005). The effect of bird droppings on the C/N value is superficial, and already at the depth of 25-30 cm the C/N value is at the same level at the cormorant sites and the control.

In general, the phosphorus content decreases with increasing depth, Table 2. The phosphorus content in the control is typical for a forest soil in Denmark. The subsoil content of about 200 ppm is about the average for subsoil horizons for sandy Weichsel tills (Damgaard, 2005). The slightly higher contents in the upper layer may be due to weathering of primary minerals or previous manuring of the areas in the 19th century.

The top layer at cormorant$_{24}$ is extremely rich in phosphorus, exceeding the nitrogen content in the horizon more than three fold, but also in the soil layer below, the total phosphorus content exceeds the nitrogen content. In cormorant$_{12}$, the phosphorus content in the top layer is only one tenth of that in cormorant$_{24}$, but seven times higher than in the control. In the soil layer below, cormorant$_{12}$ contains about three times the amount of phosphorus found in the control site. To the depth of one metre, cormorant$_{24}$ contains 3.9 kg of phosphorus per m^2, cormorant$_{12}$ 1.5 kg of phosphorus per m^2 and the control 0.4 kg of phosphorus per m^2. This means that cormorant$_{24}$ contains about ten times more phosphorus than the control within the uppermost 1 metre of the soil, while cormorant$_{12}$ only contains three to four times more phosphorus than the control. This difference between the three sites is probably due to the high input of phosphorus from the bird droppings, which are rich in phosphorus. According to Hutchinson (1950), cormorant droppings contain about 12% nitrogen and 6% phosphorus (13.1% P_2O_5). It should therefore be expected that the soils heavily contaminated by bird droppings should contain more nitrogen than phosphorus, but that is not the case. At cormorant$_{24}$, one m^2 of the soil contains 3.9 kg of phosphorus to the depth of one metre but only 2.4 kg of nitrogen and at cormorant$_{12}$ one m^2 of the soil contains almost the same amount of phosphorus and nitrogen to the depth of one metre, i.e. 1.5 kg and 1.7 kg respectively. The soil at the control shows a more common relationship between nitrogen and phosphorus as it contains three times as much nitrogen as phosphorus.

Table 4: *C/N-values and C/P values at the sites cormorant$_{24}$, cormorant$_{12}$ and control. The figures are based on five replicates.*

Depth cm	Cormorant$_{24}$		Cormorant$_{12}$		Control	
	C/N	C/P	C/N	C/P	C/N	C/P
A1 0-5	8	2	9	9	13	65
A2 5-10	10	16	9	16	15	60
A3 25-30	14	8	12	15	12	60
B 70-80	12	5	*	4	*	20

The reason for the relative enrichment of the soil by phosphorus compared to nitrogen is the fixation of phosphorus to calcium and iron and aluminium(hydr)oxides in the soil and the leaching of nitrogen from the profile as nitrate and organic nitrogen and degassing due to denitrification or evaporation as NH_3. Because the pH in the soil is low, it must be expected that phosphorus is mainly fixed by iron and aluminium(hydr)oxides. As there is a limited amount of iron and aluminium(hydr)oxides in the

Table 5: ***Permille plant available phosphorus, potassium and calcium at the sites cormorant$_{24}$, cormorant$_{12}$ and control. The figures are based on five replicates.***

	P	K	Ca
	g/kg	g/kg	g/kg
Cormorant$_{24}$			
A 0-5	3.22	2.42	13.52
A 5-10	0.78	0.55	1.76
A 25-30	0.78	0.39	0.90
B 70-80	0.40	0.20	0.82
Cormorant$_{12}$			
A 0-5	0.81	0.39	1.64
A 5-10	0.50	0.27	1.30
A 25-30	0.34	0.16	1.10
B 70-80	0.06	0.03	0.74
Control			
A 0-5	0.06	0.08	0.88
A 5-10	0.09	0.05	0.84
A 25-30	0.03	0.04	0.64
B 70-80	0.03	0.04	0.74

Table 6: *Kg/m^2 plant available phosphorus, potassium and calcium in relation to soil depths 0-50 cm and 0-100 cm.*

	P Kg/m^2	K Kg/m^2	Ca Kg/m^2
0-50 cm			
Cormorant$_{24}$	0.48	0.29	0.94
Cormorant$_{12}$	0.26	0.13	0.73
Control	0.03	0.03	0.42
0-100 cm			
Cormorant$_{24}$	0.82	0.46	1.64
Cormorant$_{12}$	0.31	0.15	1.36
Control	0.05	0.06	1.05

soil, an extreme input of phosphorus to the soil will saturate the iron and aluminium(hydr)oxides with phosphorus, and phosphorus will be leached from the soil. The high phosphorus content in all four soil layers in cormorant$_{24}$ and the uppermost 3 soil layers in cormorant$_{12}$ compared to control shows that the cormorant soils are saturated with phosphorus as demonstrated by (Breuning-Madsen et al., 2008).

Plant available phosphorus, potassium and calcium

The cormorants raise the concentration of plant available nutrients in the soils below their nests compared to the control. Especially in cormorant$_{24}$ there is a significant raise in the nutrient level, most clearly expressed for phosphorus and potassium. In the topsoil of cormorant$_{24}$ the concentration of P is about 50 times higher than in control and the K concentration is about 30 times higher. For calcium it is about 15 times. For P and K the influence of the cormorants seems to be deeper than 80 cm as the P and K concentration there are 13 and 5 times higher respectively compared to control. For Ca the effect is almost absent in that depth. In fact it is only in the uppermost 5 cm that cormorant$_{24}$ has a Ca concentration that is more than twice the Ca-content in the control.

The effect of the cormorants in the 12 years nesting area is not as big as for cormorant$_{24}$, and for all three components the effect of the cormorants is almost absent in the depth of 70-80 cm. For the three sections above 70-80 cm that means within the uppermost half metre of the soil, there is a clear increase in P and K concentration compared to control. In that part of the soil P-concentration is slightly less than 10 times higher than in the control, K is almost 5 times higher than the control, Table 5. In none of the four sections in cormorant$_{12}$ the Ca-concentration is twice as much as in control showing the the cormorants have only a limited influence on the Ca-content in the soil, except for the organic rich uppermost 5 cm in cormorant$_{24}$.

Table 6 shows the content of Ca, P and K to the depth of 50 cm and 100 cm. As for the concentrations there is a big increase in the P and K content for cormorant$_{24}$ compared to control and with cormorant$_{12}$ in between. Again the difference is less for Ca compared to P and K. There are no major changes in the relationship between P, K and Ca at the tree sites investigated, making the calculation to the depth 50 cm or 100 cm.

Electric conductivity and herb species

The huge amount of nutrients in the cormorant-influenced soils might increase the electric conductivity (EC) of the soil water if the production of salts from the bird droppings

Table 7: *The electric conductivity (EC) in dS/m for the three sites cormorant$_{24}$, cormorant$_{12}$ and control.*

Depth in cm	Cormorant$_{24}$	Cormorant$_{12}$	Control
A1 0-5	7.3	5.4	0.7
A2 5-10	6.6	4.0	0.5
A3 25-30	4.7	4.3	0.4
B 70-80	3.8	3.3	0.1

exceeds the leaching of salts during wintertime. This might have great impact on vegetation because non-salt-tolerant plants will disappear and salt tolerant plants will take over. As Vorsø is situated in a humid area where more than half of the annual precipitation is percolating through the soil profile to the ground water, electric conductivity in the soils should be low. This is demonstrated in Table 7 where the EC in the control is 0.7 dS/m or less. At cormorant$_{24}$ and cormorant$_{12}$, the EC is significantly higher than in the control, and highest in cormorant$_{24}$. It is often stated that non-salt-tolerant plants begin to suffer and disappear when EC measured by the pasta method exceeds 2 dS/m. Thus, soils with an EC of more than 2 or 4 dS/m are often classified as saline soils, and the yield for different crops like onions and other vegetables is reduced (Bohn et al., 2001). At higher EC-values such as 7dS/m, the yield of crops like maize and wheat is reduced. It can be concluded that the cormorants have changed the soil into saline soils even though the soils are located in a humid area characterized by leaching of salts and nutrients. Although the EC decreases at all three sites with depth, the cormorant sites remain salty to the depth of more than 80 cm.

The high EC at the cormorant sites greatly influences the plant community as many plants present in Denmark are unable to grow in a rather acid, nutrient-rich and salty environment. Therefore, the forest on Vorsø has changed due to the presence of the cormorants (Dal et al., 1991), and differences in the plant community at the three sites must be expected.

Table 8 shows the result of a study of herbs present in October 2004 and in October 2006 at the three sites. As the study was carried out in October, the number of herbs present might be limited compared to a study performed in summertime. Still, the study gives an impression of the species community and an idea of the influence of cormorants on the plant community.

The site cormorant$_{24}$ is characterized by a single big oak tree that hosts all the nests. At the sampling time, the tree was dead but still hosted 13 nests. The plant community below the tree has to adapt to very special and rare conditions: a high salt level and a nutrient-rich environment that is very acid at the same time. Below the dead tree, the plant density was very low and in the central part bare soil dominates. Surrounding the cental part a narrow ring of herbs was detected before elder (*sambucus nigra)* took over. The

Table 8: *The herb vegetation at the three sites cormorant$_{24,}$ cormorant$_{12}$ and control.*

Cormorant$_{24}$	Cormorant$_{12}$	Control
Gálium aparíne, L.	Artemísia vulgáris, L.	Aegopódium podagrária, L.
Holcus lanátus, L.	Circaéa lutetiána, L.	Ficária verna ssp., Hudson
Poa triviális L.	Dáctylis glomeráta L.	Gálium aparíne, L.
Rumex obtusifólius L.	Festuca altissima, All.	Geum urbánum, L.
Stellária média, (L.) Vill	Holcus lanátus, L.	Poa nemoralis, L.
Urtíca dioíca, L.	Leucanthemum vulgare, Lam	Stachys sylvática, L
	Poa trivialis, L.	Urtíca dioíca, L.
	Roegneria canina, L.	
	Rumex obtusifólius L.	
	Stellária média, (L.) Vill.	
	Taraxacum sp.	
	Urtíca dioíca, L.	

number of herbs was limited to six species, all salt-tolerant species that have adapted to very nutrient-rich conditions (Mikkelsen, 1980). Similar results were obtained by Mun (1997) in South Korea, studying a heron (*Ardea cinerea*) colony. Mun found nine plant species under a heron colony compared to 14 at the control site. The plant species at the two sites were different, and Mun suggested that the reason for the change in vegetation was partly a change in soil chemistry and partly a change in influx of sunlight. Wait et al. (2005) obtained similar results studying cormorants in the California Gulf.

Many of the trees in the surroundings of the colony are also dead or badly damaged by the cormorants. It is not clear whether the main reason is physical damage to the branches and twigs, excrements deposited on the leaves or changes in the soil chemistry or a combination of the three factors.

At cormorant$_{12}$, four ashes are the nest trees for the cormorant colony. All four trees are still alive, probably because of the low density of nests and the shorter time the colony has existed. The herb vegetation at cormorant$_{12}$ is more dense and shows a bigger diversity than at cormorant$_{24}$, indicating that the impact of the cormorants is not as big as at cormorant$_{24}$. Five out of the six species present at cormorant$_{24}$ are also present at cormorant$_{12}$, the additional species at cormorant$_{12}$ also being adapted to salty and nutrient-rich conditions. The greater species diversity is probably due to the lack of a 5 cm thick organic rich horizon in the top layer which characterizes cormorant$_{24}$, the lower content of nitrogen and phosphorus in the soil and a somewhat lower electric conductivity compared to cormorant$_{24}$. Only *Urtica dioica* recurred when the species composition at cormorant$_{12}$ was compared with the control site. This clearly indicates that the high nutrient status and relatively high salt concentration in the soil at cormorant$_{12}$ also have a clear impact on the vegetation. The difference between the control and cormorant$_{12}$ might also to some degree be due to differences in the light and space, as the vegetation cover was denser at the control than at cormorant$_{12}$, giving less light to the ground surface at the control. It can be concluded that cormorant colonies can change the vegetation cover below the nest trees considerably.

Conclusion

The soil chemistry was studied at three sites on Vorsø in Horsens Fjord, one site was situated in an area that had hosted a cormorant colony for 24 years and with a high density of nests, one site was located in an area that had hosted a cormorant colony for 12 years and with a low density of nest and the last site had no inputs from cormorants. By comparing the chemical composition of the soil at the three sites, it became clear that cormorants have a great impact on soil chemistry. The total carbon content was much higher at cormorant$_{24}$ than at the two other sites. In the uppermost one metre of the soil, cormorant$_{24}$ contained about 25 kg of carbon per m^2, while it was about 15 kg per m^2 at the two other sites. The influx of cormorant excrements and nesting material had developed a 5 cm thick organically rich top soil layer at cormorant$_{24}$. The analysis of the nitrogen content to the depth of one metre showed that cormorant$_{24}$ contained 2.2 kg of nitrogen per m^2, cormorant$_{12}$ 1.5 kg of nitrogen per m^2 and the control 1.1 kg of nitrogen per m^2, showing a clear relationship between the density and duration of the cormorant activity and the nitrogen content in the soil. The bird droppings seem to have a great impact on the soil chemistry because the bird droppings have a low C/N value and pH. Thus, the C/N value and pH are lower in the top soil horizons at the cormorant sites compared to the control site. For example, at the cormorant sites, the C/N value was about 8 compared to 13 at the control site. The acid bird droppings have decreased the pH, and the lower part of the A horizon has a pH (H_2O) below 4.0, although the nutrient content is high. At the control site, pH is about one unit higher. The content of phosphorus has strongly increased at the cormorant sites, especially at cormorant$_{24}$. Here, the total phosphorus content in the top soil was just below 5% or about 80 times more than that found at the control site.

The concentration and content of plant available P and K in cormorant$_{24}$ are much higher compared to control and with cormorant$_{12}$ in between. This is not the case for Ca where the content and concentration in cormorant$_{24}$ are only about twice of that found in control and with cormorant$_{12}$ in between.

The nutrient-rich bird droppings have raised the salt content in the soil profiles at the cormorant sites, and the electric conductivity is above 4dS/m in most of the horizons – about ten fold that measured in the samples from the control site. The high salt content has a significant impact on the plant community, and at cormorant$_{24}$ only six herbs species were recognized. They were all salt-tolerant plants that can grow in extremely nutrient-rich soils. At cormorant$_{12}$, more plant species were recognized, indicating that at sites with extreme salt concentrations the plant diversity is low. The species at cormorant$_{12}$ are not the same as those found at the control, indicating that also a medium salt content influences the plant community although differences in competiveness between species concerning light and space might also have some influence.

By comparing the soil chemistry at the three sites, it must be concluded that the impact of cormorants on the soil chemistry is significant and highly depends on the density of bird droppings and the time of colony existence.

Acknowledgement

The authors thank laboratory technician Stina Rasmussen, Department of Geography and Geology, University of Copenhagen, for handling the soil analyses, and professor Ole Borggaard, Faculty of Life Sciences, University of Copenhagen, for valuable discussion on phosphorus retention in soils. The data are complied within the current laws of Denmark. We acknowledge the comments of two anonymous referees.

References

Anderson, W.B. & Polis, G.A. (1999): Nutrient fluxes from water to land: Seabirds affect plant nutrient status on Gulf of California islands. Oecologia 118: 324-332.

Bohn, H.L., McNeal, B.L. & 0'Connor, G.A. (2001): Soil Chemistry, 3rd edition. New York, John Wiley & Sons, Inc.

Bregnballe, T. & Gregersen, J. (1995): Development of the breeding population of Cormorant *Phalacrocorax carbo senensis* in Denmark 1938-1994. Dansk Ornitologisk Forenings Tidsskrift 89: 119-134. [in Danish with English summary]

Bregnballe, T., Engström, H., Knief, W., van Eerden, M.R., van Rijn, S., Kieckbusch, J.J. & Eskildsen, J. (2003): Development of the breeding population of Great Cormorants *Phalacrocorax carbo senensis* in the Netherlands, Germany, Denmark, and Sweden during the 1990s. Vogelwelt 124: 15-26.

Bremner, J.M. (1996): Nitrogen-Total. Pp. 1085-1089 in: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T. & Summer, M.E. (eds.): Methods of Soil Analysis Part 3. Chemical methods. Madison, Soil Science Society of America and American Society of Agronomy.

Breuning-Madsen, H., Ehlers, C.B. & Borggaard, O.K. (2008): The impact of perennial cormorant colonies on soil phosphorus status. Geoderma 148: 51-54.

Dal, T., Fabricius, P., Nielsen, J. (1991): The forest of Vorsø, Denmark: Succession towards a natural, deciduous forest influenced by breeding cormorants. Journal of Botany 11: 641-649.

Damgaard, T.B. (2005): The phosphorus content in Danish soils. Unpublished master's thesis, Royal Veterinary and Agricultural University, Copenhagen. [in Danish]

Day, P.R. (1965): Particle fractionation and particle-size analysis. Pp. 545-567 in: Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E. & Clark, F.E. (eds): Methods of Soil Analysis. Agronomy No. 9. Madison, American Society of Agronomy.

Frich, P., Rosenørn, S., Madsen, H. & Jensen, J.J. (1997): Observed Precipitation in Denmark, 1961-90. Copenhagen, DMI Technical Report 97-8.

Halberg, K. (1996): Flora og vegetation på naturreservatet Vorsø 1930-1992 [Flora and vegetation at the nature reserve Vorsø 1930-1992]. Flora og Fauna 101: 79-100. [in Danish]

Hansen, K. (1996): Dansk felt flora [Danish field flora]. København, Gyldendal. [in Danish]

Hogg, E.H. & Morton, J.K. (1983): The effect of nesting gulls on the vegetation and soil of islands in the Great Lakes. Canadian Journal of Botany 61: 3240-3254.

Houmark-Nielsen, M. (1987): Pleistocene strategraphy and glacial history of the central part of Denmark. Meddelelser fra Dansk Geologisk Forening 36: 1-189

Hutchinson, G.E. (1950): Survey of existing knowledge of biogeochemistry. 3. The biogeochemistry of vertebrate excretion. New York, Bulletin of the American Museum of Natural History 96.

Ishida, A. (1997): Effects of inhabitation of the Great Cormorant (Phalacrocorax carbo) on forest ecosystems – a basic study for conservation and management of the habitat. Nagoya University Forest Science 16: 75-119.

IUSS Working Group WRB (2006): World reference base for soil resources 2006. FAO, Rome, World Soil Resources Reports 103.

Krogh, L., Nørgaard, A., Hermansen, M., Greve, M., Balstrøm, T. & Breuning-Madsen, H. (2003): Preliminary estimates of contemporary soil organic carbon stocks in Denmark using multiple datasets and four scaling up methods. Agriculture, Ecosystems & Environment 96: 19-28.

Laursen, E.V., Thomsen, R.S. & Cappelen, J. (1999): Observed Air Temperature, Humidity, Pressure, Cloud Cover and Weather in Denmark – With Climatological Standard Normals, 1961-90. Copenhagen, DMI Technical Report 99-5.

Ligeza, S. & Smal, H. (2003): Accumulation of nutrients in soils affected by perennial colonies of piscivorous birds with reference to biogeochemical cycles of elements. Chemosphere 52: 595-602.
Madsen, H.B. & Platou, S.W. (1983): Land use planning in Denmark. Nordic Hydrology 14: 267-276.
Madsen, H.B. & Munk, I. (1987): The influence of texture, soil depth and geology on pH in farmland soils – A case study from southern Denmark. Acta Agriculturæ Scandinavica 37: 407-418.
Mikkelsen, V.M. (1980): Planteøkologi og danske plantesamfund [Plant ecology and Danish plant communities]. København, DSR Forlag, Den Kgl. Veterinær- og landbohøjskole. [in Danish]
Mun, H.T. (1997): Effects of colony nesting of Adrea cinerea and Egretta alba modesta on soil properties and herb layer composition in Pinus densiflora forest. Plant and Soil 197: 55-59.
Nelson, D.W. & Sommers, L.E. (1996): Total carbon, Organic Carbon and Organic Matter. Pp. 961-1010 in: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T. & Summer, M.E. (eds.): Methods of Soil Analysis Part 3. Chemical methods. Madison, Soil Science Society of America and American Society of Agronomy.
Olsen, S.R. & Sommers, L.E. (1982): Phosphorus. Pp. 403-430 in: Page, A.L., Miller, R.H. & Keeney, D.R. (eds.): Methods of Soil Analysis Part 2. Chemical and Mineralogical Properties. Madison, Soil Science Society of America and American Society of Agronomy.
Raunkiær, C. (1910): Formationsundersøgelse og formationsstatistik. Botanisk Tidskrift 30: 20-132. [in Danish]
van Reeuwijk, L.P. (1995): Procedure for soil analysis. ISRIC and FAO, Rome, Technical paper 9.
Rhoades, J.D. (1996). Salinity: Electrical Conductivity and Total Dissolved Solids. Pp. 417-435 in: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T. & Summer, M.E. (eds.): Methods of Soil Analysis Part 3. Chemical methods. Madison, Soil Science Society of America and American Society of Agronomy.
Sobey, D.G. & Kenworthy, J.B. (1979): The relationship between herring gulls and the vegetation of their breeding colonies. Journal of Ecology 16: 193-268.
Soil Survey Staff (1998): Key to soil taxonomy. Soil conservation service – United States Department of Agriculture. Blacksburg, Virginia, Pocahontas Press, Inc.
Speir, T.W. & Cowling, J.C. (1984): Orthogenetic soils of the Cape Bird Adelie penguin rookeries, Antarctica. Polar Biology 2: 207-212.
Thomas, G.W. (1996): Soil pH and Soil Acidity. Pp. 475-490 in: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T. & Summer, M.E. (eds.): Methods of Soil Analysis Part 3. Chemical methods. Madison, Soil Science Society of America and American Society of Agronomy.
Wait, D.A., Aubrey, D.P. & Anderson, W.B. (2005): Seabird guano influences on desert islands: Soil chemistry and herbaceous species richness and productivity. Journal of Arid Environments 60(4): 681-695.