

# The complexity of ecological impacts induced by great cormorants

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**Abstract** Following decades of global extermination, the general population of the great cormorant (*Phalacrocorax carbo* L.) is on the rise. The lack of regular predators, highly skilled fish rapacity, rapid metabolism, significant rate of excretion and ability to form large nesting colonies on relatively small areas lead to numerous environmental consequences of cormorant presence. Here we comprehensively review the occurrence and distribution of this species and, in particular, its multi-faceted impact on terrestrial and aquatic ecosystems and the main routes through which these impacts are being manifested. The bird-induced chemical loading and its biological and ecological consequences, and the effects on microbial pollution and pathogen dispersion are discussed in particular. The need for further investigation to fully elucidate

particular effects is stressed throughout the paper. It is concluded that the environmental effects of great cormorants are rather complex, can lead to serious ecosystem modifications and that the presence of these birds should be taken into consideration in ecological assessment and monitoring.

**Keywords** Cormorants · Nutrient cycling · Microbial pollution · Eutrophication · Biodiversity

## Introduction

Great cormorants (*Phalacrocorax carbo* L.) are avian top-predators characterized by a global distribution encompassing Asia, Africa, Australia and New Zealand, North America and Europe (Fig. 1). Easily identified due to their long bills, black plumage and webbed feet, they forage on marine and freshwater ecosystems. Their diet is almost exclusively composed of a wide range of fish species varying in size, but usually reflecting the seasonal availability of prey at a particular site. Recognized for their highly skilled fish predation, they were largely exterminated and their number remained low over the decades (Ostman et al., 2012; Skov et al., 2014). However, over the past 40 years, a great rise in the population has been observed (van Eerden & Gregersen, 1995; Bzoma et al., 2003; White et al., 2011; Russell et al., 2012; van Eerden et al., 2012). Several reasons appear to be responsible for this phenomenon among

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**Fig. 1** World distribution (marked black) of great cormorant (*Phalacrocorax carbo*) (based upon del Hoyo et al., 1992)

which the most important include the decision to protect these birds in numerous countries, their high degree of ecological adaptation, lack of regular predators in the environment, ability to forage on marine and freshwater ecosystems, increase in fish biomass due to the eutrophication of surface waters and global climate changes (Cramp & Simmons, 1998; Skov, 2011; White et al., 2011).

Changes in the population status of cormorants have raised serious concerns as to the consequences of their presence in the environment. As these birds are generally gregarious, appear collectively, gather in flocks, nest in colonies and can feed on a relatively large area on various aquatic ecosystems simultaneously, they may constitute a very important biological factor triggering environmental changes (Kolb et al., 2010; Klimaszyk et al., 2015b). Therefore, the impact of cormorants on various elements of both the terrestrial and aquatic environment has been largely addressed in different studies. The birds breed on land but forage on water so they represent a very important intermediate link in some food webs (Gwiazda et al., 2010; Skov et al., 2014) and a factor facilitating the relocation of matter and possibly also some microbial agents between aquatic and terrestrial ecosystems (Marion et al., 1994; Huang et al., 2014). A large number of potential outcomes of cormorant presence has been demonstrated, including soil fertilization, eutrophication, changes in terrestrial and aquatic vegetation, loss of biodiversity, dispersion of certain

pathogens and food web modifications. To date these studies have rarely addressed more than one aspect of the environmental activity of cormorants. However, in order to attain a full assessment of the complex influence and ecological risks exhibited by these birds, a more multi-faceted approach and review should be attempted.

The present review aims to comprehensively present the potential effects of cormorants on different aspects of environmental functionality. The main characteristics of these birds, essential to understand their impacts, are also summarized. The bird-induced chemical and biological transformations of terrestrial and aquatic ecosystems and routes through which they are mediated are discussed. The emphasis is put particularly on nutrients loading and its biological consequences, and microbial dispersion. Finally, the paper raises several unresolved issues which, if addressed in future research, may help achieve an understanding of the environmental role of cormorants and develop a reasonable approach to the management of these species.

### Main characteristics of great cormorant

#### Sub-species of *Phalacrocorax carbo*

According to del Hoyo et al. (1992), six sub-species of *P. carbo* can be distinguished: *P. c. carbo* L., *P. c.*

*sinensis* Blumenbach., *P. c. novaehollandiae* Stephens, *P. c. maroccanus* Hartert, *P. c. hanedae* Staunton and *P. c. lucidus* Licht. It should, however, be noted that the taxonomy of the *Phalacrocorax* is currently subject to dynamic turnover and that cormorant sub-species should be separated only upon the basis of phylogenetic analyses and not morphological features (Kennedy & Spencer, 2014). In Europe, the existence of two sub-species *P. c. carbo* and *P. c. sinensis* characterized by small genetic distance was confirmed using analyses of microsatellites (Goostrey et al., 1996) and mitochondrial DNA (Marion & Le Gentil, 2006). Moreover, there is some evidence for the existence of a third sub-species *P. c. norvegicus* Marion & Le Gentil on this continent whose colonies were initially identified near the Baltic Sea in Norway, France, Sweden, Denmark and Netherlands (Marion & Le Gentil, 2006). Further studies are necessary to elucidate the contribution of this sub-species to the total European *P. carbo* population estimated at over 400,000 breeding pairs with circa 90% represented by *P. c. sinensis* (Bregnballe et al., 2014).

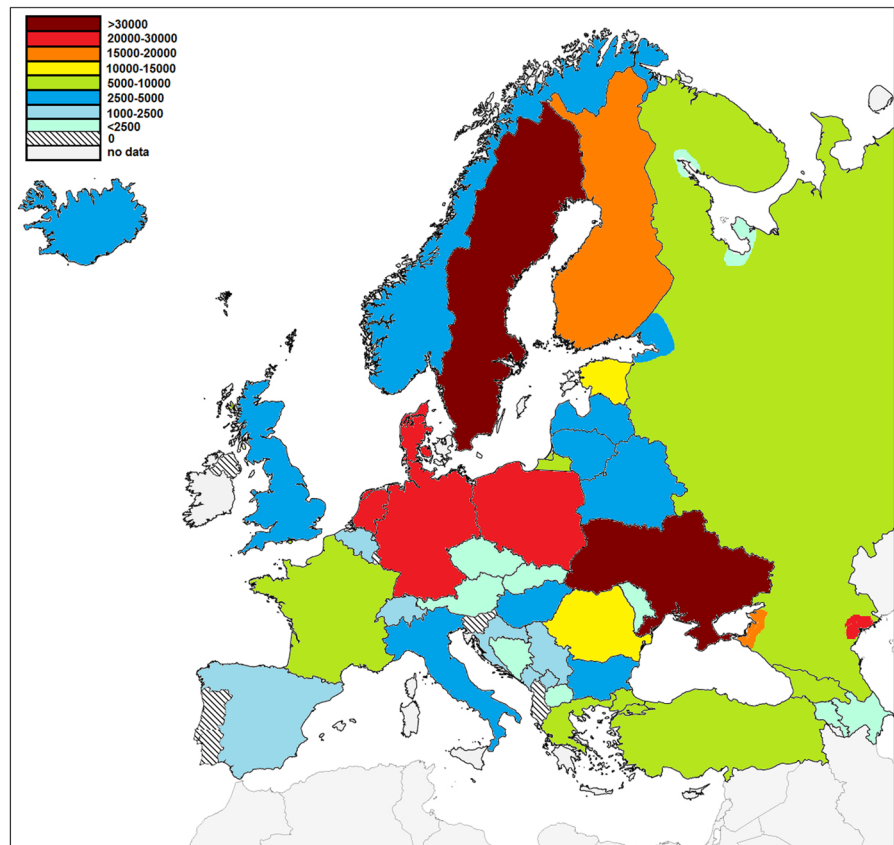
#### Global status of *Phalacrocorax carbo* populations

The great cormorant has an extremely wide distribution and occurs on every continent with the exception of South America and Antarctica (del Hoyo et al., 1992). Colonies in North America are restricted to the north-east part although some individuals may winter further south as far as the tip of the Florida peninsula. Breeding colonies are also found in Western Greenland. In Europe, the great cormorant can be found along most of the Atlantic coast as well as thorough the Mediterranean, Central and Eastern Europe (Fig. 2). In Africa, the bird winters on the northern coast as well as along the River Nile, and breeds year-round on the north-west coast, in pockets of Central-east and South Africa. In Asia, summer breeding is noted in patches through the central part of the continent up to Eastern China, while wintering occurs in Southeastern Asia—India and Southern China. Finally, the great cormorant can also be found breeding in New Zealand and throughout the Australian continent with the exception of the central regions. The range of *P. carbo* sub-species demonstrates geographical differentiation although partially overlaps (del Hoyo et al., 1992; Cramp & Simmons, 1998; BirdLife International, 2014; Bregnballe et al., 2014).

As obligatory fish predators, cormorants, perceived as competitors with human fisheries, were largely exterminated over the years. The bird colonies were habitually destroyed and the birds were frightened so as to avoid the devastation of flora, mainly tree species—a consequence of building nests and droppings deposition, discussed later in detail. Additionally, the widespread use of DDT pesticide until the end of 1970s could also have contributed to a decrease in the reproductive success of cormorants (Boudewijn & Dirksen, 1995). Altogether, these factors resulted in a global decline in the great cormorant population (Ostman et al., 2012) and this species was considered to be extinct in many European countries (van Eerden & van Rijn, 1997). However, over the last 40 years, a steady and worldwide increase in the number of these birds has been observed (van Eerden & Gregersen, 1995; Bzoma et al., 2003; White et al., 2011; Russell et al., 2012; van Eerden et al., 2012) with almost 2.9 million individuals estimated at the beginning of the twenty first century (Wetlands International, 2006). From the early 1980s, the European population of *P. carbo* sub-species was growing by 18% annually (Winney et al., 2001) with several thousand breeding pairs counted in 1980, through to 200,000 pairs estimated in 2000 and more than 400,000 in 2013 (Trolliet, 1999; Bregnballe et al., 2014; Fig. 2). However from the beginning of 2010s, the number of cormorants in some European regions (Holand, Belgium) stabilized or decreased (Norway, Sweden, Poland, Croatia, Hungary, Danube delta region) (Bregnballe et al. 2014). The population of the Asian sub-species *P. c. hanedae* and African *P. c. lucidus* rapidly started to grow in the late 1980s and stabilized at the beginning of the twenty first century (Kameda et al., 2003; Yesou & Triplet, 2003). The population of *P. c. lucidus* was estimated at 40,000 individuals in Coastal West Africa, 15,000 in Coastal South Africa and 500,000 in Central and Eastern Africa (Delany et al., 2007; van Roomen et al., 2014), while the population of *P. c. hanedae* was estimated at 100,000 individuals (Brazil, 2009). In North America, the population of *P. carbo* is stable unlike the double-crested cormorant *Phalacrocorax auritus* Lesson, whose number is rising (Hebert et al., 2014).

The increase in the number of *P. carbo* can be observed in some regions despite a high mortality rate among juvenile individuals estimated at 25–68% in the first year of life, 13% in the second and an annual

**Fig. 2** Estimated number of nesting pairs of great cormorant (*Phalacrocorax carbo*) in Europe (based upon Bregnballe et al., 2014)



12% death ratio in older birds (Frederiksen & Bregnballe, 2000; Stempniewicz et al., 2000). As cormorants are long-lived species, it is not easy to predict the changes of their population although competition for breeding space or food does not play a key role in dynamics of their global population (Sæther et al., 2005).

Increases in population sizes of *P. carbo* are most likely to be a result of several concurrent reasons such as

- (i) the decision taken by the governments of numerous countries to protect this species,
- (ii) the discontinuation of the use of DDT and other harmful chemicals (Dirksen et al., 1995),
- (iii) the increase in availability of food resources resulting from cultural eutrophication and intensive fishery, both leading to profound changes in fish structure such as a prevalence of small cyprinids over predators and large-sized specimens (Psuty, 2010),

- (iv) the high plasticity of cormorants leading to ecological adaptation,
- (v) lack of natural enemies, with the exception of humans and very sporadically, white-tailed eagles (van Eerden & Voslamber, 1995) and
- (vi) global warming leading to more rapid decay of the ice cover of freshwaters thereby increasing the availability of feeding areas and prolonging the chick rearing period (White et al., 2011; Skov, 2011).

#### Colonies of *Phalacrocorax carbo*

Cormorants are considered as “central place foragers”—they form roosting or breeding colonies and forage up to distances of 10–15 km from it, flying nearly 50 km daily back and forth (Paillisson et al., 2004; Goc et al., 2005; van Eerden et al., 2012).

The breeding colonies are formed at peaceful locations, far from direct human impacts. In coastal regions, the birds nest on inshore islands, cliffs, stacks,

boulders and, occasionally, artificial structures. Inland they occupy islands, peninsulas, river forks and areas near lakes, and build nests on bushes and mainly deciduous (e.g. willow, alder, birch) and coniferous trees (e.g. pines), rarely on the ground. Up to 50 nests may be found in one tree, depending on the tree species. The colonized sites are often reused over the years (del Hoyo et al., 1992; Bzoma, 2011; van Eerden et al., 2012). Usually, after the colony has been established, the number of nests increases annually until their maximum is reached. The number of birds that make up the breeding colonies can vary from a few to several thousand. In Europe (Fig. 2), the largest colonies can be found at Kąty Rybackie on the Baltic Sea coast of Poland and at an islet near the Crimean peninsula in Ukraine (Bzoma et al., 2003).

Roosting colonies are always situated on the banks of aquatic environments and, particularly in wintering periods, can be very numerous; bird densities may even exceed those observed in breeding colonies (Dirksen et al., 1995; Klimaszuk et al., 2015a).

The abundance of cormorants is particularly regulated by the trophic state of aquatic ecosystems. The lowest bird densities are found near oligotrophic (low productivity and fish stock) and hypertrophic (low transparency alters the predation) water bodies. Eutrophic waters, on the other hand, offer large numbers of fish (small-sized cyprinids, predominantly) and are often inhabited by cormorants (van Eerden & Voslamber, 1995; Skov, 2011; van Eerden et al., 2012).

## The effect on terrestrial ecosystems

### Soil chemistry

Considering their daily food intake (0.4 kg) and faeces deposition (20–50 g per day), cormorants excrete considerable loads of chemicals. Because they spent only about 4 h daily on foraging, over 80% of faeces are deposited beneath their roosts and nests (Marion et al., 1994; Mukherjee & Board, 2001; Goc et al., 2005). Various contents of N and P in cormorant droppings are given in the literature ranging from 3.2–14.5 to 5.9–14%, respectively, with a mean N:P ratio of 1.5:1 (Marion et al., 1994; Kameda et al., 2000; Goc et al., 2005; Gwiazda et al., 2010; Klimaszuk et al., 2015a). A single bird deposits over

4 g of N and 2.5 g of P daily beneath its roost or nest. Depending on cormorant density, the reported loads of deposited nutrients vary over a range of 181–1120 and 112–786 kg ha year<sup>-1</sup> for N and P, respectively (Kameda et al., 2000; Goc et al., 2005; Klimaszuk et al., 2015b). These numbers are underestimated because they do not consider the delayed loads which are first accumulated on plants and then washed out during rainfall. Moreover, a small quantity of nutrients can be introduced with cormorant pellets, usually swallowed fish which later decay on the ground and release nutrients. Finally, significant nutrient enrichment occurs through forest litter generated during cormorant activity. Cormorants may be responsible for the accumulation of as much as 2000 kg ha<sup>-1</sup> of forest litter per month (Hobara et al., 2001; Osono et al., 2006). Such an extreme amount results from over 12 kg of twigs and branches used by the birds to build a single nest (Goc et al., 2005).

It is beyond any doubt that the abovementioned activities must result in significant soil chemistry alterations. The most significant changes include nutrient enrichment and acidification. The chemical properties of the top soil layer are extremely modified, while the degree to which the deeper horizons are altered depends on the density of the colony and the time that has elapsed since it was established as well as the properties of the deposited chemicals, microbial activities and conditions of the ambient environment. Long-lasting colonies may alter the soil chemistry up to a depth of 1 m.

Over time cormorants, especially in dense colonies, increase N and P content in soil layers to extreme extents (Ligeża & Smal, 2003; Hobara et al., 2005; Kolb et al., 2012; Rush et al., 2013; Litaor et al., 2014; Klimaszuk et al., 2015b). However, even a small cormorant flock can induce a short-term rise in their concentrations, usually restricted to period the birds are present (Klimaszuk et al., 2015b). In the case of dense breeding or roosting colony areas, the levels of nutrients in the top soil layer are very high all year round, even when the birds are absent.

The faeces-originating N occurs primarily in the form of uric acid, readily biochemically degraded to ammonia—an initial substrate of nitrification. In this form, N accumulates mainly in the surface soil layer (Ligeża & Smal, 2003) and may undergo volatilization (Mizutani & Wanda, 1988; Mulder & Keall, 2001; Ligeża & Smal, 2003; Hobara et al., 2005). The

intensity of this process depends, however, on variables such as pH, soil moisture and temperature (Loder et al., 1996). As cormorant faeces also acidify soils, volatilization is of lower importance (Kameda et al., 2000; Breuning-Madsen et al., 2010) and transformation to nitrates occurs instead (Hobara et al., 2001). The nitrates of faecal origin can accumulate not only in the top layer but also at considerable depths (Ligeża & Smal, 2003). Upper horizons are usually characterized by a prevalence of organic N (Ishida, 1996; Ligeża & Smal, 2003). Generally, the content of N in organic and inorganic form in soils beneath cormorant colonies are increased 10-fold due to the birds' activity (Ligeża & Smal, 2003; Hobara et al., 2005; Breuning-Madsen et al., 2010; Klimaszuk et al., 2015b). Sporadically, the N content can be even higher, e.g. one study reported over 140 times higher organic N (10,000 vs. 70 mg kg<sup>-1</sup>) in the top soil horizon (up to 5 cm depth) than at a control site (Klimaszuk et al., 2015a). The bird-originating P delivered to the ground is less mobile in the soil horizon than N and usually accumulates in the top layer (Ligeża & Smal, 2003; Hobara et al., 2005; Breuning-Madsen et al., 2008). The total P has been found to increase from 30 to 250-fold compared to control areas. The longer the colony has been established, the more accumulation of P in soils occurs (Ligeża & Smal, 2003; Breuning-Madsen et al., 2008; Klimaszuk et al., 2015a).

Apart from N and P, the cormorant colonies deliver significant amounts of carbon (Breuning-Madsen et al., 2010; Klimaszuk & Joniak, 2011) and potassium (Ligeża & Smal, 2003). Both elements are utilized by floral and microbial communities in the upper layers but they may also infiltrate and accumulate in the deeper soil horizons. Cormorant activity may increase the potassium content 10–30-fold (Ligeża & Smal, 2003; Klimaszuk et al., 2015a). Colonized areas are also usually characterized by increased total (TOC) and dissolved (DOC) carbon (Ishida, 1996; Osono et al., 2006). Soil enrichment in DOC and TOC results from a high accumulation of plant debris (Osono et al., 2006) and is usually observed after long term and very intensive cormorant activity (Breuning-Madsen et al., 2010).

#### Terrestrial ecosystems

Cormorants significantly affect the terrestrial vegetation overgrowing the areas they inhabit and colonize. The impact is of dual origin:

- (i) mechanical destruction and withering of trees;
- (ii) the deposition of faeces and various kinds of debris leading to chemical and physical alteration of soils and groundwater.

During the first stages of colonization, the gradual delivery of N, P and K, predominantly in faeces, fertilizes soil and promotes primary production. This may even be reflected in an increase in the number of plant species (Żółkoś & Meissner, 2008). However, at some point the chemical properties of soils begin to greatly exceed tolerable levels and plant biodiversity significantly decreases (Boutin et al., 2011). This is mostly due to altered root absorption capacities in a highly fertile habitat and as a result growth is subsequently reduced. Deposition of uric acid and increased NH<sub>4</sub> concentration lead to soil acidification (Pearson & Steward, 1993), the conditions under which the uptake of cations is largely decreased (VanDijk et al., 1989). Seed germination is also usually affected under such conditions (Ishida, 1997; Ellis et al., 2006; Żółkoś & Meissner, 2008). Changes of soil and groundwater have a particular impact on herbs and shrubs with shallow root systems. Cormorants may also affect trees through direct deposition of faeces on leaves, effectively decreasing their photosynthetic activity and respiration, and leading to retarded growth. After long dry periods, up to 80% of the vegetation in the colony area can be covered with faeces. Finally the vegetation, mainly trees, receives mechanical damage. One pair of cormorants uses approximately 13 kg of twigs, leaves and needles. For comparison, a single matured pine consists of 24–30 kg of needles and small twigs (Goc et al., 2005). Therefore, colonization is usually followed by heavy tree defoliation (Ishida, 1996). Coniferous trees are generally more susceptible to cormorant activity than deciduous species, which tolerate loss of branches and leaves to some extent. Regardless of the species, the colonized areas are, however, eventually subject to floral withering and decay. The decreased health status of trees may induce pest invasion and further exacerbate unfavourable changes of vegetation within the colony (Goc et al., 2005).

Nest density and subsequent faeces deposition are the most important factors affecting plant abundance and biodiversity within sites colonized by cormorants. The total number of plants, including herbs and shrubs, may decrease up to as much as 70%, while

forest-specific floral communities may disappear altogether. Instead, nitrophilous species such as *Sambucus nigra* L. overgrow the area due to high N deposition from bird droppings (Ishida, 1996; Kolb et al., 2012; Klimaszuk et al., 2015b). Their dense development may decrease light availability within the floor zone and thereby limit the growth of herbaceous species (Ishida, 1996; Hofmeister et al., 2009; Klimaszuk et al., 2015c) which grow only within shrub gaps and are usually represented by highly nitrophilous grasses such as *Calamagrostis epigejos* L., *Poa nemoralis* L. and *Poa trivialis* L. (Goc et al., 2005). Importantly, the occurrence of alien plant species has been recorded within former cormorant colonies (Klimaszuk et al., 2015b). In summary, the influence of bird activity on terrestrial vegetation is complex and may lead to long-lasting changes in biodiversity and species composition (Fig. 3).

Changes in vegetation, decrease of primary production and tree vitality together with an increase of forest litter accumulation can also trigger changes in the zoocenoses of the forest floor. The abundance and diversity of herbivorous insects is reduced while fungivorous, xylophagous species and scavengers are usually promoted (Kolb et al., 2012). Fish regurgitated by cormorants provide an additional source of food. Cormorants do not re-collect regurgitated fish but herons become commensals and exploit that food resource (Goc et al., 2005). Carrion abundance at the colonies also attracts vertebrate predators and scavengers. Counts show that the density of foxes (*Vulpes vulpes* L.), raccoons (*Nyctereutes procyonoides* Gray) and crows is higher in the vicinity of cormorant colonies (Goc et al., 2005). Standing defoliated trees in former colonies are used by predatory birds as observation points. Interestingly, some carnivorous birds may treat cormorants as “food vending machines”. As observed in the field, two adult white-tailed eagles (*Haliaeetus albicilla* L.) frightened socially fishing cormorants, which regurgitated fish and flew away. The eagles started to feed on the dozens of dead fish floating on the lake surface. Similarly, a white stork (*Ciconia ciconia* L.) was observed to vocally scare nesting cormorants at the colony and feed upon regurgitated food (personal observations).

## Transport of nutrients from terrestrial to aquatic environment

The chemical compounds deposited with cormorant faeces and partially washed from accumulated litter, being mobile to some extent, can partially enter nearby aquatic ecosystems (Fig. 3). During dry periods, they may additionally undergo chemical transformation, particularly into mineral forms. Washing out, leaching and transport, is promoted by precipitation and occurs in two major ways: more rapidly through surface runoff and more slowly with groundwater (Gwiazda et al., 2010; Klimaszuk & Rzymiski, 2013a). The contribution of each depends mainly on the land morphology, substrate permeability and vegetation. Steep inclination and cormorant-induced deforestation promote chemical wash-out, particularly with runoff (Chang, 2012). The concentrations of chemicals in runoff and groundwater are highly dependent on bird density and the length of time that the colony or roosts have been established (Klimaszuk et al., 2015a, b, c).

Surface runoff from cormorant colonies is usually characterized by extremely high nutrient concentration, exceeding as much as 17 mg l<sup>-1</sup> for total P and 300 mg l<sup>-1</sup> for total N (Klimaszuk et al., 2015b). In comparison with similar sites unaffected by birds, the concentrations of ammonium can be increased 50-fold, nitrates 30-fold, organic N more than 60-fold and total P 45-fold. Additionally, the runoff from colonies may increase DOC content and high electrical conductivity as well as low and almost always acidic pH (Klimaszuk & Joniak, 2011). Unsurprisingly, the highest levels of chemical compounds are observed within breeding season but, importantly, they may remain high even during periods when the birds do not occupy the colony area (Klimaszuk et al., 2015b).

Similarly to runoff, the chemical composition of groundwater outflowing from colonized areas or sites with cormorant roosts may be significantly enriched. This is particularly important in flat areas where the groundwater-table is located near the soil surface. In such cases, the groundwater can contain as much as over 25 mg l<sup>-1</sup> of total P (with over 75% being orthophosphates) and over 250 mg l<sup>-1</sup> of total N (Klimaszuk, 2012; Klimaszuk et al., 2015a). Contrary to surface runoff, the nutrient concentrations of groundwater are constantly increased throughout the

year, even in periods when birds are absent. Moreover, few years after the birds have ceased to nest or roost at such a site, the levels of chemical compounds in groundwater may still remain elevated (Klimaszyk et al., 2015c).

## The effects on aquatic ecosystems

### Quality of surface waters

Like other waterfowl, cormorant may affect surface waters in a variety of ways (Fig. 3). Interestingly, in the case of these birds, this impact may have a dual role and promote eutrophication or, conversely, prevent this process. The latter effect is, however, observed at small ponds only. At such water bodies, intensively foraging cormorants may drastically decrease the number of fish and simultaneously increase the density of zooplankton, which is followed by limited phytoplankton development and an improvement in water transparency (Gmitrzuk, 2004). Such a phenomenon may be called “cormorant-induced biomanipulation” but it can only occur when birds do not nest or roost in proximity of pond at which they forage. Otherwise, levels of nutrient supply from colony area to the aquatic ecosystem may exceed this excluded by foraging birds (McCann et al., 2000).

Undoubtedly, cormorants may decrease the pool of biogenic elements through fish consumption (Ligeza & Smal, 2003). It has been calculated that eating 400 g of fish daily, a single cormorant will extract 40 g of N and 12 g of P from an aquatic ecosystem (Hahn et al. 2007). If one considers how abundant cormorant flocks may be, such an exclusion of nutrients from the entire ecosystem budget can be significant (Mukherjee & Board, 2001). On the other hand, cormorants may forage on various aquatic ecosystems (located within 30 km of the colony) but still deposit most of their faeces over the relatively small area of the colony (Cramp & Simmons, 1998). While some portion of these loads is immobilized within the terrestrial ecosystem through plant uptake, microbial degradation and soil fixing or may volatilize into the atmosphere, significant quantities of chemical elements can be transferred with runoff and groundwater. This eventually results in the inflow of high levels of

nutrients into surface waters, mostly littoral zones. Even though the surface runoff from the colony area is rather an episodic event, its impact on the chemistry of an aquatic ecosystem cannot be ignored. As already discussed in the previous section, the runoff delivers significant loads of nutrients, particularly during the vegetative season, and may therefore promote phytoplankton development. In some cases, the amount of total N and P transported from a relatively small colony area to a lake can be 50-fold higher than the load from its natural catchment. Thus, 1.2 ha of colony may deliver a load of nutrients equal to those delivered from 60 ha of forested catchment. The input of chemicals from some colonized areas can even constitute up to 20% of the total nutrient balance of a large lake (Klimaszyk et al., 2015a) and for small and shallow reservoirs, up to 70% and over 35% of total P and N content, respectively (McCann et al., 1997; McCann et al., 2000). Large cormorant colonies may play significant roles in the nutrient budgets of nearby lakes (Klimaszyk et al., 2014, 2015a, b).

In surface waters, the chemical and biological impacts of cormorant activity are revealed only within the direct littoral area. The magnitude by which the nutrient concentrations are increased is strictly associated with the number of birds inhabiting the colony (Nakamura et al., 2010a, b) although the maximum peaks of some parameters, such as total P or chlorophyll, may be observed with some delay, usually a month after the highest number of cormorants is observed (Nakamura et al., 2010a). Changes in nutrient chemistry can promote primary production through algae growth, as well as changes in the macrophyte community—discussed in detail in the subsequent sub-section.

The morphological and biological complexity of large and deep water reservoirs successfully prevent aquatic biocoenoses from rapid changes induced by cormorant colonies. Even though the littoral zone in the proximity of bird-inhabited areas may reveal increased concentrations of bioavailable nutrients during the breeding or roosting season (Kolb et al., 2010; Klimaszyk, 2012; Klimaszyk et al., 2014, 2015a), wave action and water currents dilute them throughout the ecosystem to an extent which does not exhibit any biological changes (Gwiazda et al., 2014). Therefore, biological outcomes of cormorant activities are more likely to be observed in smaller and shallow reservoirs.



## Primary producer communities

The significant nutrient fluxes from the catchment area may lead to increased concentrations and N and P availability in littoral water, followed by a promotion of primary production and significant shifts in the phytoplankton community, including excessive development of potentially harmful algae such as certain species of cyanobacteria. As cormorant colonies have been shown to enrich groundwater and surface runoff with nutrients and their colonies can play a relevant role in the total lake balance of N and P, it could be anticipated that they may induce the abovementioned processes. Littoral zones near colonies have been found to contain increased concentrations of orthophosphates, ammonium and nitrates—the nutrient forms readily utilized by phytoplankton (Klimaszyk, 2012; Klimaszyk et al., 2014; Klimaszyk et al., 2015a). The availability of N from cormorant faeces for macro- and microalgae has also been demonstrated using  $^{15}\text{N}$  signatures (Kolb et al., 2010).

Unfortunately, no studies on phytoplankton assemblages have been conducted for littoral zones undergoing the pressure of a breeding cormorant colony. Incomplete conclusions can be drawn from direct observations of a small roosting colony (<55 birds) near which a significantly higher share of chlorophytes was observed at a site in the vicinity of the cormorant roost. Other groups cyanobacteria, diatoms, dinophytes, euglenophytes, chrysophytes cryptophytes and conjugatophytes did not differ in terms of their contribution to the phytoplankton community (Gwiazda et al., 2010). Other investigations at a larger roosting colony found a nearly sixfold increase in chlorophyll-a content in a soft-water lake over a 10-year period (Klimaszyk et al., 2015a). During this time, the number of roosting birds increased from 600 in 1998 to over 1000 in 2009. A high pigment level was, inter alia, a result of blooming *Microcystis aeruginosa* Kützing (Klimaszyk et al., 2015a)—a species known to potentially produce microcystins, compounds recognized for their toxicity in eukaryotes (Rzymiski et al., 2015). Further studies are necessary to fully elucidate the relationship between cormorant activities (particularly forming large colonies) and the phytoplankton community.

The impact of cormorants on aquatic macrophytes has been little studied. It was, however, demonstrated that the establishment of a cormorant colony near a

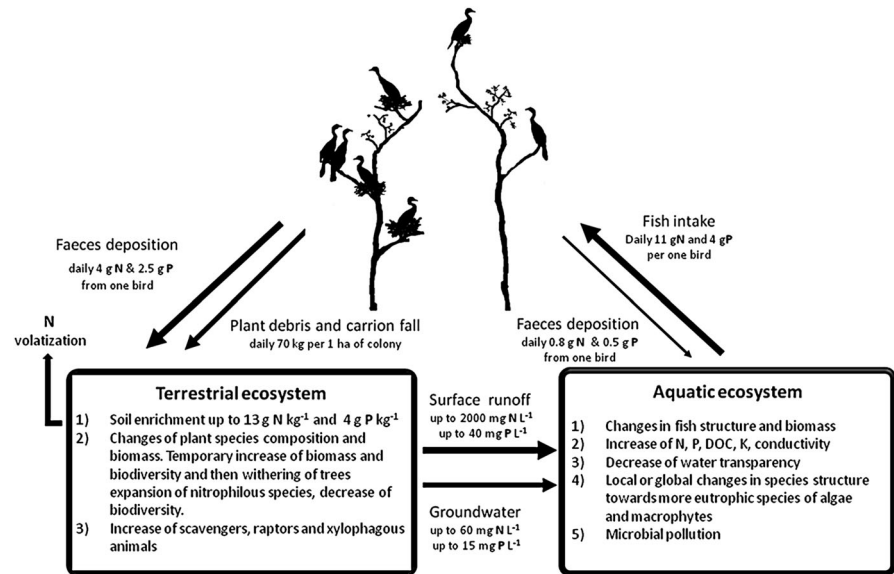
shallow soft-water lake followed by a decade of increase in bird abundance resulted in an increase of nutrient concentrations in the littoral area and a decrease of species characteristic for oligotrophic reservoirs, *Littorella uniflora* (L.) Asch. and *Myriophyllum alterniflorum* DC., largely replaced by eutrophic *Ceratophyllum demersum* L. and *Elodea canadensis* L. It is highly probable that these changes were brought about by a simultaneous increase in phytoplankton (as demonstrated by a several-fold increase in chlorophyll-a content) leading to decreased water transparency (Klimaszyk et al., 2015a).

## Fish communities

Despite the fact that cormorants may enrich their diet with crustaceans, amphibians and even polychaetes, their primary prey is fish (Scott & Duncan, 1967; del Hoyo et al., 1992; Boudewijn & Dirksen, 1998; Leopold & van Damme, 2003). Cormorants are indeed characterized by a high predation abilities resulting from their swimming speed (over  $1\text{ m s}^{-1}$ ), great diving velocity (up to  $4\text{ m s}^{-1}$ ) and depth (usually 2–5 m but occasionally even up to 20 m or more) as well as the ability to hunt socially (van Eerden & Voslamber, 1995; Ropert-Coudert et al., 2006). Water turbidity appears to be one of the main factors affecting hunting behaviour (solitary or social fishing) and limiting the foraging activity of cormorants (van Eerden & Voslamber, 1995; Strod et al., 2008). The highly developed predatory skills of these birds have led to the belief that they can effectively compete with fishermen for resources—their food intake ranges from 250 to  $800\text{ g day}^{-1}$  (Dirksen et al., 1995; Gremillet & Dey, 1996; Carss & Marquiss, 1997). Numerous human-cormorant conflict cases have been reported over the years at various fishery sites: rivers, lakes, freshwater aquaculture ponds, coasts and coastal aquaculture sites. Cyprinids and salmonids are among the main group of fish over which these conflicts have arisen although over 70 fish species inhabiting various aquatic environments and of different body sizes (lengths from 30 mm to over 700 mm) have been reported to serve as food for cormorants.

The conditions affecting preference of cormorants to feed on particular fish species and the effects of these birds on fish abundance and communities have been widely investigated over the years and described

**Fig. 3** The complexity of great cormorant (*Phalacrocorax carbo*) impact on terrestrial and aquatic ecosystem



in excellent review papers by Cowx (2003) and Van Eerden et al. (2012). Some studies also addressed economic damage induced by great cormorants foraging on fish farms and suggested several methods to reduce cormorant-human conflicts (Opačak et al., 2004; Gwiazda, 2010). An excellent guideline on cormorant control is prepared by Russell et al. (2012).

#### Aquatic invertebrate communities

Very limited data are available on the potential effect of *P. carbo* on benthic macroinvertebrates and zooplankton. However, it is anticipated that to some extent particularly larger breeding colonies may have an impact on these communities. Firstly, the increase in nutrient availability and subsequent promotion of algae growth may stimulate zooplankton density and abundance. Such an effect has already been demonstrated experimentally in ponds fertilized with commercially available bird guano corresponding to the density of *P. auritus* of 10 birds per m<sup>2</sup>. Stimulated growth of phytoplankton resulted in a time lag in consumer response to increased resources despite predation pressure (Butts et al., 2013). Since *P. auritus* and *P. carbo* defecate comparable nutrient loads, these effects can be, at least partially, extrapolated to the situation at the littoral in the proximity of densely populated colonies of great cormorants. In a study conducted on the Baltic Sea, the abundance and total biomass of such invertebrates as *Jaera albifrons*

Leach, chironomids and *Gammarus* sp. increased significantly in areas with high cormorant nest densities (Kolb et al., 2010). As these species feed on micro- and macroalgae, it is likely that cormorants promote nutrient loading and subsequent phytoplankton biomass in inhabited areas. On the other hand, one could suggest that cormorant foraging may induce top-down control in the aquatic food web. Cormorants could theoretically promote large-sized zooplankton (Cladocera) growth through the consumption of fish species or limit it through the elimination of predatory fish populations. It should be, however, stressed that the diet of *P. carbo* is very non-specific and that these birds can prey far from the colony (up to 30 km radius) and, simultaneously, on various aquatic ecosystems (Marion et al., 1994; Kameda et al., 2006). Moreover, food web relationships are subject to a complex function of endogenous and exogenous factors and, especially for larger water bodies, cannot be explained by the single element of a bird presence (Sydeman et al., 2010). Further field studies are necessary to fully explain the influence of great cormorants on food web relationships.

#### Role in pathogen dispersion

Birds, particularly migratory ones, represent an important factor in the harbouring and dispersal of microorganisms, including pathogens (Graczyk et al., 1998). The microbiota of birds has been shown to be

affected by many different factors, such as infections and general health status, diet and local microbial communities in the environment (Gabriel et al., 2005; Santos et al., 2012). The main route through which the birds can take part in the dispersion of various microorganisms, including bacteria, viruses and protozoa, is faeces excretion. As already discussed in the previous sections, cormorants can deposit a large amount of faeces within the colony area and partially, directly into nearby surface waters. Therefore, they may play a profound role in the dispersion of some microorganisms including bacteria, viruses and parasites, and the further consequences of this dispersion such as a decrease in the sanitary quality of water, animal diseases and potential threat to human health. So far, several studies have investigated whether cormorants may be a significant host of some pathogens and contribute to their further environmental dispersion (Table 1).

The fact that cormorants may contribute to microbial pollution in the environment is supported by a significantly increased number of coliform bacteria, common components of commensal intestinal flora (DeVincent, 2004) within the colony and nearby areas. Coliforms, composed of genera belonging to the family of *Enterobacteriaceae*, are a group of rod-shaped, non-spore forming Gram-negatives. In general, the identification of these bacteria in the environment does not unambiguously pose a relevant threat to human health but usually indicates that other pathogenic microorganisms may be present. Additionally, some strains of these bacteria, particularly *Escherichia coli*, are characterized by a high degree of virulence in humans. Therefore, it is of general public interest to keep the number of coliform in the environment as low as possible. The *E. coli* strains isolated from the European population of *P. carbo* have not only been shown to be highly resistant to antibiotics such as cephalosporins and fluoroquinolones but the highly virulent O25b-ST131 clone has been identified among them (Literak et al., 2010; Tausova et al., 2012). Altogether, these findings indicate that cormorants may spread epidemiologically important antimicrobial-resistant bacteria through their droppings.

The presence of pandemic faecal bacteria in *P. carbo* can raise serious health concerns if one considers that these birds can cause extreme increases in the coliform and *E. coli* counts in groundwater beneath the

colony. The larger the colony and number of cormorant nests, the more significant pollution of groundwater is observed. The greatest density of coliforms and *E. coli* is usually found in groundwater within the area of the breeding colony and can reach over 40,000 and 2000 counts per 100 cm<sup>3</sup>, respectively, but maximally rise to more than 70,000 and 6000 counts per 100 cm<sup>3</sup>, respectively. Lower levels of bacterial contamination were noted for groundwater outflowing from perennial colonies. Although the microbial pollution of surface runoff occurring at cormorant colony sites has not yet been investigated, it is rather likely that it is also characterized by a largely increased number of total coliform and *E. coli*. Apart from the direct deposition of faeces, runoff and groundwater represent two major routes through which cormorant colonies can increase the bacterial number in nearby lakes. The mean bacterial densities usually form a gradient from the highest number recorded near the colony to the lowest found in the central part of the lake (Klimaszyk, 2012; Klimaszyk & Rzymiski, 2013b). Besides *E. coli*, the *Enterobacteriaceae*, the littoral water near colonies can be characterized by a relatively high share of *Enterobacter gergoviae*, *Klebsiella oxytoca*, *Serratia odorifera*, *Citrobacter freundii*, *Enterobacter cloacae* and *Rahnella aquatilis* (Wiśniewska et al., 2007).

No association between the activities of *P. carbo* and the presence of pathogenic species from the *Shigella* and *Salmonella* genus in lake water has been found (Wiśniewska et al., 2007). On the other hand, a recent study has found *S. typhimurium*, a leading cause of human gastroenteritis (McClelland et al., 2001), in a few cormorants shot in Switzerland (Albini et al., 2014). Further studies are required to fully elucidate the role of these birds in the dispersion of this pathogen. In turn, species of *Chlamydiae*, a widely spread obligate intracellular genus of bacteria, have not so far been identified in *P. carbo* although only one study has investigated their presence in this species (Albini et al., 2014).

As well as bacteria, *P. carbo* populations can constitute a source for the spread of some pathogenic viruses. To date, only a few studies have addressed the presence of the avian influenza virus (AIV) in *P. carbo*. Moreover, from at least four pathogenic AIV subtypes (Leong et al., 2008; Zhang et al., 2014), only H5 and H7 have been investigated. AIV positive antibodies were not found in a serosurvey conducted

**Table 1** Pathogens potentially dispersed by great cormorant (*Phalacrocorax carbo*)

Pathogen	Place of identification	Notes	Potential threats
<b>Bacteria</b>			
<i>E. coli</i>	Poland, Czech Republic (as an intestinal commensal, it is spread anywhere the cormorant is present)	O25b-ST131 clone was isolated. The increased <i>E. coli</i> counts were observed in lake littoral and groundwater within the colony area	Predominantly serious urinary tract infections (O25b-ST131)
<i>S. enterica</i>	Switzerland	Low prevalence	Serious gastroenteritis
<b>Viruses</b>			
Avian influenza virus H5	North-western area of the Caspian Sea	Very low prevalence	Highly pathogenic avian influenza transmitted between birds and to mammals resulting in death
Avian paramyxovirus serotype-1	North-western area of the Caspian Sea, France (antibodies), Switzerland (antibodies)		Newcastle disease in poultry and wild birds. Clinical symptoms in human
West Nile virus	North-western area of the Caspian Sea	Mosquitoes are prime vectors; birds are main hosts	West Nile fever. Rarely neurological symptoms
<b>Fungi</b>			
Microsporidia	Slovakia	<i>Encephalitozoon cuniculi</i> was identified	Intestinal parasitosis, diarrhoea
<b>Protozoan parasites</b>			
<i>Cryptosporidium</i> sp.	Hungary, Netherlands	The exact genotype was not determined	Intestinal parasitosis, diarrhoea
<i>Giardia</i> sp.	Hungary	The exact genotype was not determined	Intestinal parasitosis, diarrhoea

For references see sub-section ‘The role in pathogens dispersion’

in Switzerland (Albini et al., 2014) nor were they found in France (Artois et al., 2002). H5 subtype was, however, detected using molecular methods (RT-PCR) in cloacal lavages of *P. carbo* inhabiting the north-western area of the Caspian Sea (Iashkulov et al., 2008) but its prevalence was very low (below 5.0%). Because AIV in other cormorant species such as *P. magellanicus*, *P. atriceps* (Gallo et al., 2013) and *P. harrisi* (Travis et al., 2006) has not been identified, and only a very low prevalence of AIV was found in *P. auritus* for which AIV-specific antibodies and AIV matrix protein were positive only sporadically (Cross et al., 2013), it can be suggested that this group of birds is unlikely to be involved in the circulation of the virus. However, more extensive surveys on *P. carbo*, including populations from other parts of the world, are necessary before any definitive conclusions can be drawn. Moreover, the presence of other potentially pathogenic AIV subtypes in cormorants, H9N2 (Sun & Liu, 2014) and novel H10N8 (Zhang et al., 2014), requires further attention.

Great cormorants may represent a suitable host for avian paramyxovirus serotype-1 (APMV-1), the

causative agent of virulent Newcastle disease (ND) (Alexander, 2000). ND has a history of dramatic devastations in poultry, and it remains a major problem for poultry industries in many countries as well as an economic burden due to the costs associated with vaccinations and biosecurity requirements (Degefa et al., 2004). Furthermore, APMV-1 is potentially transmissible to humans, particularly poultry workers are at higher risks of clinical symptoms of infection (Nelson et al., 1952). *P. carbo* have been already implicated in ND outbreaks among domestic poultry in Scotland (Blaxland, 1951). A study conducted by Schelling et al. (1999) on the Swiss *P. carbo* population found APMV-1 positive antibodies in nearly 20% of sampled cormorants but failed to isolate the virus. A more recent investigation in Switzerland failed to isolate APMV-1 in tested individuals (Albini et al., 2014). The virus was, however, found in birds inhabiting the Volga estuary during the 2001, 2003 and 2006 virological monitoring programmes (Usachev et al., 2006; Iashkulov et al., 2008). It appears that this particular *P. carbo* population may represent a steady host of this

pathogen as the virus was also detected in cormorants inhabiting this region in the 1970s (L'vov et al., 1977). Another study found APMV-1 positive antibodies in French *P. carbo* but did not attempt to isolate the virus (Artois et al., 2002). Nevertheless, species, *P. auritus*, has a long record of morbidity and mortality events, the results of this survey indicate that ND occurs within this population. Despite the wide distribution of *P. carbo*, no other studies have analysed the presence of APMV-1 or APMV-1 antibodies in these birds. Another cormorant associated with ND outbreaks in North America (White et al., 2015). ND has also been recorded for *P. aristotelis*. Therefore, further studies are necessary to fully understand the exact role of *P. carbo* in AMPV-1 dispersion in particular areas. As ND spreads mainly through bird droppings (Hines & Miller, 2012), the large amount of faeces deposited by *P. carbo* within the colony area may represent a significant source of environmental dispersion of the virus from infected individuals.

Apart from AIV and AMPV-1, other viruses exhibiting certain pathogenicities to humans and animals have been investigated and detected sporadically. The Dhori virus, which was found to cause similar symptoms to the H5 virus in mice (Li et al., 2008), was isolated from a single *P. carbo* individual in the Caspian Sea region. Sera of sampled cormorants in this region contained specific antibodies against Sindbis and Tahini and West Nile (WNV) viruses (Iashkulov et al., 2008); the latter was also isolated using molecular analyses (L'vov et al., 2006). Of these three, WNV is the most important as regards health protection because it currently has a nearly worldwide distribution encompassing Africa, Asia, Australia, the Middle East, Europe and in the United States, causing regular disease outbreaks among humans (Gray & Webb, 2014). Nevertheless, due to the low number of virological monitoring surveys, the role of *P. carbo* in the dispersion of these viruses cannot be clearly resolved.

Surprisingly, the dispersive stages of intestinal parasites such as *Cryptosporidium* sp. and *Giardia* sp. have been very little studied in *P. carbo*. These protozoan species are of special concern as they are ubiquitously identified in terrestrial and aquatic animals, including birds. The dispersion of oocysts/cysts occurs through faeces and finally, an infectious dose for these enteropathogens is low (Karanis et al., 2007). As various species and/or genotypes and even

subgenotypes of *Cryptosporidium* and *Giardia* differ in their degree of infectivity and virulence (Carey et al., 2004; Thompson, 2004), the estimation of their real health threat is not possible without molecular analyses. In spite of this the presence of these parasites in *P. carbo* has only been investigated very rarely. A survey conducted in Hungary found *Cryptosporidium* sp. oocyst and *Giardia* sp. cyst in bird faeces but this study examined only one cormorant sample and failed to sequence the exact species of these parasites (Plutzer & Tomor, 2009). *Cryptosporidium* oocysts (but not *Giardia* cysts) were also detected in *P. carbo* faeces collected in the Netherlands at a prevalence of 20% and mean concentration of 64 oocysts per g, high enough to significantly contribute to the contamination of a water reservoir (Medema, 1999). There is no doubt that further studies are required to fully assess the impact of cormorant colonies on the dispersion of both *Giardia* cysts and *Cryptosporidium* oocysts, particularly in aquatic environments. Because cormorants inhabiting one colony can simultaneously forage on different water bodies but their faeces are mainly deposited within a relatively small area, these birds may be potentially responsible for the transmission of some intestinal parasites between ecosystems. It should be stressed that *Cryptosporidium* and *Giardia* do not only represent a threat to human health as some genotypes are capable of infecting mammals, birds, reptiles and amphibians as well as fish, both wild and farmed (Sitjà-Bobadilla et al., 2005; Šlapeta, 2009). Therefore, analyses of faecal samples should be accompanied by genotyping investigations to fully assess the ecological risks.

## Conclusions

It is likely that the populations of *P. carbo* in some world regions may still continue to rise, although this seems to be no longer occurring in parts of Europe. Taking into consideration the fact that ecosystems self-regulate through homeostasis and hysteresis, the populations are unlikely to keep growing indefinitely, although the factors controlling populations (other than anthropogenic ones) are not well understood. Cormorants, once nearly extinct due to human fears and reluctance, represent an important connection between land and water for the cycling of nutrients and may have significant roles in the structuring of land

and aquatic communities. Nevertheless, the complex effects of cormorants on aquatic and terrestrial ecosystems need to be taken into account in ecological assessment and monitoring.

**Updates** This article was updated on February 9, 2016. The reference ‘van Eerden & Gregersen, 1995’ was corrected.

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## References

- Albini, S., L. Konrad, B. Sigrist, R. Güttinger, R. Keller & R. K. Hoop, 2014. Shedding of zoonotic pathogens and analysis of stomach contents in great cormorants (*Phalacrocorax carbo sinensis*) from Switzerland between 2007 and 2012. *Schweizer Archiv für Tierheilkunde* 156: 389–394.
- Alexander, D. J., 2000. Newcastle disease and other avian paramyxoviruses. *Revue Scientifique et Technique* 19: 443–462.
- Artois, M., R. Manvell, E. Fromont & J. B. Schweyer, 2002. Serosurvey for Newcastle disease and avian influenza A virus antibodies in great cormorants from France. *Journal of Wildlife Diseases* 38: 169–171.
- BirdLife International, 2014. Species Factsheet: *Phalacrocorax carbo*. <http://www.birdlife.org>. Accessed 19 Nov 2014.
- Blaxland, J., 1951. Newcastle disease in shags and cormorants and its significance as a factor in the spread of this disease among domestic poultry. *The Veterinary Record* 47: 731–733.
- Boudewijn, T. J. & S. Dirksen, 1995. Impact of contaminants on the breeding success of the Cormorant *Phalacrocorax carbo sinensis* in The Netherlands. *Ardea* 83: 325–338.
- Boutin, C., T. Dobbie, D. Carpenter & C. E. Hebert, 2011. Effect of Double Crested Cormorant on island vegetation, seed-bank and soil chemistry: evaluating island restoration potential. *Restoration Ecology* 19: 720–727.
- Brazil, M., 2009. *Birds of East Asia: Eastern China, Taiwan, Korea, Japan, Eastern Russia*. Christopher Helm, London.
- Bregnballe, T., J. Lynch, R. Parz-Gollner, L. Marion, S. Volponi, J.-Y. Paquet, D. N. Carss & M. R. van Eerden, 2014. Breeding numbers of Great Cormorants *Phalacrocorax carbo* in the Western Palearctic, 2012/2013. IUCN-Wetlands International Cormorant Research Group Report. Scientific Report from DCE—Danish Centre for Environment and Energy No. 99.
- Breuning-Madsen, H., B. C. Ehlers & O. K. Borggaard, 2008. The impact of perennial cormorant colonies on soil phosphorus status. *Geoderma* 148: 51–54.
- Breuning-Madsen, H., C. Ehlers-Koch, J. Gregersen & C. L. Lojtnant, 2010. Influence of perennial colonies of piscivorous birds on soil nutrient contents in a temperate humid climate. *Geografisk Tidsskrift* 110: 25–35.
- Butts, A., K. Frady, K. L. Sheehah, R. J. Johnson & G. K. Yarow, 2013. Influence of Double-Crested Cormorants on Food Web Productivity in Freshwater Ponds. In: J. B. Armstrong & G. R. Gallagher (eds), *Proceedings of the 15th Wildlife Damage Management Conference*: 142–143.
- Bzoma, S., 2011. Protection of Cormorant: *Phalacrocorax carbo* in Poland. Strategy of Management of Cormorant Population in Poland—Project. Warsaw. SGGW: 74. [in Polish]
- Bzoma, S., M. Goc, T. Brylski, L. Stempniewicz & L. Iliszko, 2003. Seasonal changes and intracolony differentiation in the exploitation of two feeding grounds by Great Cormorants (*Phalacrocorax carbo sinensis*) breeding at Kały Rybackie (N Poland). *Vogelwelt* 124: 175–181.
- Carey, C. M., H. Lee & J. T. Trevors, 2004. Biology, persistence and detection of *Cryptosporidium parvum* and *Cryptosporidium hominis* oocyst. *Water Research* 38: 818–862.
- Carss, D. N. & M. Marquiss, 1997. The diet of cormorants *Phalacrocorax carbo* in Scottish freshwaters in relation to feeding habitats and fisheries. *Polish Journal of Ecology* 45: 207–222.
- Chang, M., 2012. *Forest Hydrology: an Introduction to Water and Forests*, 3rd ed. CRC Press, Boca Raton.
- Cowx, I. G., 2003. *Interactions Between Birds and Fish: Implications for Management*. Blackwell Science, Oxford.
- Cramp, S. & K. E. L. Simmons, 1998. *The Birds of the Western Palearctic*. Oxford University Press, New York.
- Cross, T. A., D. M. Arsnoe, R. B. Minnis, D. T. King, S. Swafford, K. Pedersen & J. C. Owen, 2013. Prevalence of avian paramyxovirus 1 and avian influenza virus in double-crested Cormorants (*Phalacrocorax auritus*) in eastern North America. *Journal of Wildlife Diseases* 49: 965–977.
- Degefa, T., L. Dadi, A. Yami, K. GMariam & M. Nassir, 2004. Technical and economic evaluation of different methods of Newcastle disease vaccine administration. *Journal of Veterinary Medicine. A, Physiology, Pathology, Clinical Medicine* 51: 365–369.
- Delany, S., D. A. Scott, T. Helminck & G. Martakis, 2007. Report on the conservation status of migratory waterbirds in the agreement area. Third Edition. AEW Technical Series No. 13.
- del Hoyo, J., A. Elliott & J. Sargatal, 1992. *Handbook of the Birds of the World. Ostrich to Ducks*, Lynx.
- DeVincent, S. J., 2004. Wildlife and the ecology of antimicrobial resistance. In Baer, C. K. (ed.), *Proceedings of the Conference Health and Conservation of Captive and Free-Ranging Wildlife*. American Association of Zoo Veterinarians, San Diego.
- Dirksen, S., T. J. Boudewijn, R. Noordhuis & E. C. L. Martejn, 1995. Cormorants *Phalacrocorax carbo sinensis* in shallow eutrophic freshwater lakes: prey choice and fish consumption in the nonbreeding period and effects of large-scale fish removal. *Ardea* 83: 167–184.
- Ellis, J. C., J. M. Farina & J. D. Witman, 2006. Nutrient transfer from sea to land: the case of gulls and cormorants in the Gulf of Maine. *Journal of Animal Ecology* 75: 565–574.
- Frederiksen, M. & T. Bregnballe, 2000. Evidence for density-dependent survival of adult cormorants from a combined

- analysis of recoveries and resightings. *Journal of Animal Ecology* 69: 737–752.
- Gabriel, I., S. Mallet & P. Sibille, 2005. La microflore digestive des volailles: facteurs de variation et conséquences pour l'animal. *INRA* 18: 309–322.
- Gallo, L., F. Quintana & M. Uhart, 2013. Serosurvey for selected infectious agents in two sympatric species of cormorants (*Phalacrocorax atriceps* and *Phalacrocorax magellanicus*) from coastal Patagonia, Argentina. *Journal of Wildlife Diseases* 49: 492–500.
- Gmitrzuk, K., 2004. Influence of Great Cormorant on terrestrial and freshwater ecosystems of Wigry National Park. *Parki Narodowe i Rezerwaty Przyrody* 23: 129–146. [in Polish with English summary].
- Goc, M., L. Iliszko & L. Stempniewicz, 2005. The largest European colony of great cormorant on the vistula spit (N Poland)—an impact of the forest ecosystem. *Ecological Questions* 6: 93–103.
- Goostrey, A., D. N. Carss, L. R. Noble & S. B. Pierny, 1998. Population introgression and differentiation in the great cormorant *Phalacrocorax carbo* in Europe. *Molecular Ecology* 7: 329–338.
- Graczyk, T. K., R. Fayer, J. M. Trout, E. J. Lewis, C. A. Farley, I. Sulaiman & A. A. Lal, 1998. *Giardia* sp. cysts and infectious *Cryptosporidium parvum* oocysts in the feces of migratory Canada geese (*Branta canadensis*). *Applied and Environmental Microbiology* 64: 2736–2738.
- Gray, T. J. & C. E. Webb, 2014. A review of the epidemiological and clinical aspects of West Nile virus. *International Journal of General Medicine* 7: 193–203.
- Gremillet, D. & R. Dey, 1996. Determining food intake by great cormorants and European Shags with electronic balances. *Journal of Field Ornithology* 64: 637–648.
- Gwiazda, R., 2010. Carp fishponds—pressure of waterbirds on fishes. In Ciesla, M. & R. Wojda (eds), *Wielofunkcyjność gospodarki Stawowej w Polsce. Aktualne uwarunkowania*. SGGW, Warsaw.
- Gwiazda, R., K. Jarocho & E. Szarek-Gwiazda, 2010. Impact of small cormorant (*Phalacrocorax carbo sinensis*) roost on nutrients and phytoplankton assemblages in the littoral regions of submontane reservoir. *Biologia* 65: 742–748.
- Gwiazda, R., A. Woźnica, B. Łozowski, M. Kostecki & A. Flis, 2014. Impact of waterbirds on chemical and biological features of water and sediments of a large, shallow dam reservoir. *Veterinary Medicine International* 43: 418–426.
- Hahn, S., S. Bauer & M. Klaassen, 2007. Estimating the contribution of carnivorous waterbirds to nutrient loading in freshwater habitats. *Veterinary Medicine International* 52: 2421–2433.
- Hebert, C. E., J. Pasher, D. V. C. Veseloh, T. Dobbie, S. Dobbyn, D. Moore, V. Minelga & J. Duffe, 2014. Nesting cormorants and temporal changes in island habitats. *Veterinary Medicine International* 78: 307–313.
- Hines, N. L. & C. L. Miller, 2012. Avian paramyxovirus serotype-1: a review of disease distribution, clinical symptoms, and laboratory diagnostics. *Veterinary Medicine International*. doi:10.1155/2012/708216.
- Hobara, S., T. Osono, K. Koba, N. Tokuchi, S. Fujiwara & K. Kameda, 2001. Forest floor quality and N transformations in a temperate forest affected by avian-derived N deposition. *Water Air Soil Pollution* 130: 679–684.
- Hobara, S., K. Koba, T. Osono, N. Tokuchi, A. Ishida & K. Kameda, 2005. Nitrogen and phosphorus enrichment and balance in forest colonized by cormorants: implications of the influence of soil adsorption. *Plant and Soil* 268: 89–101.
- Hofmeister, J., J. Hosek, M. Modry & J. Rolecek, 2009. The influence of light and nutrient availability on herb layer species richness in oak-dominated forests in central Bohemia. *Plant Ecology* 205: 57–75.
- Huang, T., L. Sun, Y. Wang, Z. Chu, X. Qin & L. Yang, 2014. Transport of nutrients and contaminants from ocean to island by emperor penguins from Amanda Bay. *East Antarctic Science of Total Environment* 468(469): 578–583.
- Iashkulov, K. B., M. I. Shchelkanov, S. S. L'vov, S. D. Dzhambinov, I. V. Galkina, I. T. Fediakina, B. T. Bushkieva, T. N. Morozova, D. E. Kireev, D. S. Akanina, K. E. Litvin, E. V. Usachev, A. G. Prilipov, T. V. Grebennikova, V. L. Gromashevskii, S. S. Iamnikova, A. D. Zaberezhnyi & D. K. L'vov, 2008. Isolation of influenza virus A (Orthomyxoviridae, Influenza A virus), Dhori virus (Orthomyxoviridae, Thogotovirus), and Newcastle's disease virus (Paromyxoviridae, Avulavirus) on the Malyi Zhemchuzhnyi Island in the north-western area of the Caspian Sea. *Voprosy Virusologii* 53: 34–38.
- Ishida, A., 1996. Effect of the common cormorant, *Phalacrocorax carbo*, on evergreen forest in two nest sites at Lake Biwa, Japan. *Ecological Research* 11: 193–200.
- Ishida, A., 1997. Seed germination and seedling survival in a colony of the common cormorant, *Phalacrocorax carbo*. *Ecological Research* 12: 249–256.
- Kameda, K., K. Koba, C. Yoshimizu, S. Fujiwara, S. Hobara, L. Koyama, N. Tokuchi & A. Takayanagi, 2000. Nutrient flux from aquatic to terrestrial ecosystem mediated by Great Cormorant. *Sylvia* 36: 54–55.
- Kameda, K., A. Ishida & M. Narusue, 2003. Population increase of the Great Cormorant *Phalacrocorax carbo* hanedae in Japan: conflicts with fisheries and trees and future perspectives. *Vogelwelt* 124: 27–33.
- Kameda, K., K. Koba, S. Hobara, T. Osono & M. Terai, 2006. Pattern of natural <sup>15</sup>N abundance in lakeside forest ecosystem affected by cormorant-derived nitrogen. *Hydrobiologia* 567: 69–86.
- Karanis, P., C. Kourenti & H. Smith, 2007. Waterborne transmission of protozoan parasites: a worldwide review of outbreaks and lessons learnt. *Journal of Water and Health* 5: 1–38.
- Kennedy, M. & H. G. Spencer, 2014. Classification of the cormorants of the world. *Polish Journal of Soil Science* 79: 249–257.
- Klimaszyk, P., 2012. May a cormorant colony be a source of coliform and chemical pollution in a lake? *Oceanological and Hydrobiological Studies* 41: 67–73.
- Klimaszyk, P. & T. Joniak, 2011. Impact of Black cormorant (*Phalacrocorax carbo sinensis*) on the transport of dissolved organic carbon from catchment area to lakes. *Polish Journal of Soil Science* 44: 161–166.
- Klimaszyk, P. & P. Rzymiski, 2013a. Impact of cormorant (*Phalacrocorax carbo sinensis* L.) colonies on microbial pollution in lakes. *Limnological Review* 3: 139–145.

- Klimaszyk, P. & P. Rzymiski, 2013b. Catchment vegetation can trigger lake dystrophy through changes in runoff water quality. *Annales de Limnologie-International. Journal of Limnology* 49: 191–197.
- Klimaszyk, P. & A. Brzeg, 2015. Long-term changes in the ecosystem of a lake (Lake Strzyżminkie) and an island induced by a colony of Great Cormorants (*Phalacrocorax carbo sinensis* L.). *Oceanological and Hydrobiological Studies* 44: 316–325.
- Klimaszyk, P., T. Joniak & P. Rzymiski, 2014. Roosting colony of cormorants (*Phalacrocorax carbo sinensis* L.) as a source of nutrients for the lake. *Limnological Review* 14: 111–119.
- Klimaszyk, P., R. Piotrowicz & P. Rzymiski, 2015a. Changes in the ecosystem of shallow softwater lake induced by the great cormorant roosting colony. *Journal of Limnology* 74: 114–122.
- Klimaszyk, P., A. Brzeg, P. Rzymiski & R. Piotrowicz, 2015b. Black spots for aquatic and terrestrial ecosystems: impact of a perennial cormorant colony on the environment. *Science of the Total Environment* 517: 222–231.
- Kolb, G. S., J. Ekholm & P. A. Hambäck, 2010. Effects of seabird nesting colonies on algae and aquatic invertebrates in coastal waters. *Marine Ecology Progress Series* 417: 287–300.
- Kolb, G., L. Jerling, C. Essenberg, C. Palmberg & P. A. Hambäck, 2012. The impact of nesting cormorants on plant and arthropod diversity. *Ecography* 35: 726–740.
- Leong, H. K., C. S. Goh, S. T. Chew, C. W. Lim, Y. N. Lin, S. F. Chang, H. H. Yap & S. B. Chua, 2008. Prevention and control of avian influenza in Singapore. *Annals Academy of Medicine Singapore* 37: 504–509.
- Leopold, M. F. & C. J. G. van Damme, 2003. Great cormorant *Phalacrocorax carbo* and polychaetes: can worms sometimes be a major prey of a piscivorous seabird? *Marine Ornithology* 31: 83–87.
- Li, G., N. Wang, H. Guzman, E. Sbrana, T. Yoshikawa, C. T. Tseng, R. B. Tesh & S. Y. Xiao, 2008. Dhori virus (Orthomyxoviridae: Thogotovirus) infection of mice produces a disease and cytokine response pattern similar to that of highly virulent influenza A (H5N1) virus infection in humans. *American Journal of Tropical Medicine and Hygiene* 78: 675–680.
- Ligeza, S. & H. Smal, 2003. Accumulation of nutrients in soils affected by perennial colonies of piscivorous birds with reference to biogeochemical cycles of elements. *Chemosphere* 52: 595–602.
- Litaor, M. I., O. Reichmann, E. Dente, A. Naftaly & M. Shenker, 2014. The impact of ornithogenic inputs on phosphorus transport from altered wetland soils to waterways in East Mediterranean ecosystem. *Science of the Total Environment* 473(474): 37–42.
- Literak, I., M. Dolejska, D. Janoszowska, J. Hrusakova, W. Meissner, H. Rzycka, S. Bzoma & A. Cizek, 2010. Antibiotic-resistant *Escherichia coli* bacteria, including strains with genes encoding the extended-spectrum beta-lactamase and QnrS, in waterbirds on the Baltic Sea Coast of Poland. *Applied and Environmental Microbiology* 76: 8126–8134.
- Loder III, T. C., B. Ganning & J. A. Love, 1996. Ammonia nitrogen dynamics in coastal rockpools affected by gull guano. *Journal of Experimental Marine Biology and Ecology* 196: 113–129.
- Lvov, D. K., V. N. Siurin, L. P. Nikiforov, N. V. Portianko & A. A. Sazonov, 1977. Discovery of natural foci of Newcastle disease virus in the USSR. *Voprosy Virusologii* 3: 311–316.
- Marion, L. & J. Le Gentil, 2006. Ecological segregation and population structuring of the cormorant *Phalacrocorax carbo* in Europe, in relation to recent introgression of continental and marine subspecies. *Evolutionary Ecology* 20: 193–216.
- Marion, L., P. Clergeau, L. Brient & G. Bertu, 1994. The importance of avian-contributed nitrogen (N) and phosphorus (P) to Lake Grand-Lieu, France. *Hydrobiologia* 279(280): 133–147.
- McCann, K. D., L. D. Olson & P. G. Hardy, 1997. Contribution of roosting cormorants to the nutrient budget of Lake Aldair (Ontario, Florida). *Proceedings of the Florida Lake Management Society*. Palm Beach: 89–90.
- McCann, K. D., L. D. Olson & P. G. Hardy, 2000. Water quality changes in Lake Adair following removal of roosting cormorants. *Proceedings of the Florida Lake Management Society 2000 Annual Conference*, Hawk's Cay Resort Duck Key, Florida: 54–55.
- McClelland, M., K. E. Sanderson, J. Spieth, S. W. Clifton, P. Latreille, L. Courtney, S. Porwollik, J. Ali, M. Dante, F. Du, S. Hou, D. Layman, S. Leonard, C. Nguyen, K. Scott, A. Holmes, N. Grewal, E. Mulvaney, E. Ryan, H. Sun, L. Florea, W. Miller, T. Stoneking, M. Nhan, R. Waterston & R. K. Wilson, 2001. Complete genome sequence of *Salmonella enterica* serovar Typhimurium LT2. *Nature* 413: 852–856.
- Medema, G. J. (1999). *Cryptosporidium and Giardia: New Challenges to the Water Industry*. Ph.D. Thesis. University of Utrecht.
- Mizutani, H. & E. Wanda, 1988. Nitrogen and carbon isotope ratios in seabird rookeries and their ecological implication. *Ecology* 69: 340–349.
- Mukherjee, A. & C. K. Board, 2001. Effect of waterbirds on water quality. *Hydrobiologia* 464: 201–205.
- Mulder, C. P. H. & S. N. Keall, 2001. Burrowing seabirds and reptiles: impact on seeds and soils in an island forest in New Zealand. *Oecologia* 127: 350–360.
- Nakamura, M., T. Yabe, Y. Ishii, K. Kido & M. Aizaki, 2010a. Extreme eutrophication in a small pond adjacent to a forest colonized by great cormorant (*Phalacrocorax carbo*). *Japanese Journal of Limnology* 71: 19–26.
- Nakamura, M., T. Yabe, Y. Ishii, K. Kido & M. Aizaki, 2010b. Seasonal changes of shallow aquatic ecosystems in a Bird Sanctuary pond. *Journal of Water Environment Technology* 8: 393–401.
- Nelson, C. B., B. S. Pomeroy, K. Schroll, W. E. Park & R. J. Lindeman, 1952. An outbreak of conjunctivitis due to Newcastle disease virus (NDV) occurring in poultry workers. *American Journal of Public Health and the Nations Health* 42: 672–678.
- Opačak, A., T. Florijančić, D. Horvath, S. Ozimec & D. Bodačkoš, 2004. Diet spectrum of great cormorants (*Phalacrocorax carbo sinensis* L.) at the Donji Miholjac carp fishponds in eastern Croatia. *European Journal of Wildlife Research* 50: 173–178.
- Osono, T., S. Hobara, K. Koba, K. Kameda & H. Takeda, 2006. Immobilization of avian excreta-derived nutrients and



- reduced lignin decomposition In needle and twig litter In a temperate coniferous forest. *Soil Biology and Biochemistry* 38: 517–525.
- Ostman, O., M. K. Boström, U. Bergström, J. Andersson & S. G. Lunneryd, 2013. Estimating competition between wildlife and humans—a case of cormorants and coastal fisheries in the Baltic Sea. *PLoS One* 8(12): e83763.
- Paillisson, J.-M., A. Carpentier, J. Le Gentil & L. Marion, 2004. Space utilization by a cormorant (*Phalacrocorax carbo* L.) colony in a multi-wetland complex in accordance with feeding strategies. *Comptes Rendus Biologies* 327: 493–500.
- Pearson, J. & G. R. Steward, 1993. The deposition of atmospheric ammonia and its effect on plants. *New Phytologist* 125: 283–305.
- Plutzer, J. & B. Tomor, 2009. The role of aquatic birds in the environmental dissemination of human pathogenic *Giardia duodenalis* cysts and *Cryptosporidium* oocysts in Hungary. *Parasitology International* 58: 227–231.
- Psuty, I., 2010. Natural, social, economic and political influences on fisheries: a review of the transitional area of the Polish waters of the Vistula Lagoon. *Marine Pollution Bulletin* 61: 162–177.
- Ropert-Coudert, Y., D. Gremillet & A. Kato, 2006. Swim speeds of free-ranging great cormorants. *Marine Biology* 149: 415–422.
- Russell, I., B. Broughton, T. Keller & D. Carss, 2012. The INTERCAFE cormorant management toolbox. Methods for Reducing Cormorant Problems at European fisheries. COST Action 635 Final Report III: 87.
- Rush, S. A., T. Dobbie & A. T. Fisk, 2013. Quantification of cormorant litter and nutrient deposition to Great Lakes island ecosystems. *Journal of Great Lakes Research* 39: 303–307.
- Rzyski, P., B. Poniedziałek, M. Kokociński, T. Jurczak, D. Lipski & K. Wiktorowicz, 2015. Interspecific allelopathy in cyanobacteria: cylindrospermopsin and *Cylindrospermopsis raciborskii* effect on the growth and metabolism of *Microcystis aeruginosa*. *Harmful Algae* 35: 1–8.
- Santos, S. S., S. Pardal, D. N. Proença, R. J. Lopes, J. A. Ramos, L. Mendes & P. V. Morais, 2012. Diversity of cloacal microbial community in migratory shorebirds that use the Tagus estuary as stopover habitat and their potential to harbor and disperse pathogenic microorganisms. *FEMS Microbiology Ecology* 82: 63–74.
- Sæther, B.-E., R. Lande, S. Engen, H. Weimerskirch, M. Lillegard, R. Altwegg, P. H. Becker, T. Bregnballe, J. E. Brommer, R. H. McCleery, J. Merila, E. Nyholm, W. Rendell, R. R. Robertson, P. Tryjanowski & M. E. Visser, 2005. Generation time and temporal scaling of bird population dynamics. *Nature* 436: 99–102.
- Schelling, E., B. Thur & L. Audige, 1999. Epidemiological study of Newcastle disease in backyard poultry and wild bird populations in Switzerland. *Avian Pathology* 28: 263–272.
- Scott, D. & K. W. Duncan, 1967. The function of freshwater crayfish gastroliths and their occurrence in perch, trout and shag stomachs. *New Zealand Journal of Marine and Freshwater Research* 2: 99–104.
- Sitjà-Bobadilla, A., F. Padros, C. Aguilera & P. Alvarez-Pelitero, 2005. Epidemiology of *Cryptosporidium molnari* in Spanish gilthead sea bream (*Sparus aurata* L.) and European sea bass (*Dicentrarchus labrax* L.) cultures: from hatchery to market size. *Applied and Environmental Microbiology* 71: 131–139.
- Skov, H., 2011. Waterbird Populations and Pressures in the Baltic Sea. Norden Publications, Copenhagen.
- Skov, H., N. Jepsen, H. Baktoft, T. Jansen, S. Pedersen & A. Koed, 2014. Cormorant predation on PIT-tagged lake fish. *Journal of Limnology* 73: 177–186.
- Šlapeta, J., 2009. Centenary of the genus cryptosporidium: from morphological to molecular species identification. In Ortega-Pierres, M. G. (ed.), *Giardia and Cryptosporidium: From Molecules to Disease*. CAB International, Wallingford: 31–50.
- Stempniewicz, L., M. Goc, S. Bzoma, C. Nitecki & L. Iliszko, 2000. Can timing and synchronisation of breeding affect chick mortality in the Great Cormorant? *Acta Ornithologica* 35: 35–42.
- Strod, T., I. Izhaki, Z. Arad & D. Katzhir, 2008. Prey detection by great cormorant (*Phalacrocorax carbo sinensis*) in clear and in turbid water. *Journal of Experimental Biology* 211: 866–872.
- Sun, Y. & J. Liu, 2014. H9N2 influenza virus in China: a cause of concern. *Protein and Cell* 6: 18–25.
- Sydeman, W. J., S. A. Thompson, J. A. Santora, M. F. Henry, K. H. Morgan & S. D. Batten, 2010. Macro-ecology of plankton-seabird associations in the North Pacific Ocean. *Journal of Plankton Research* 32: 1697–1713.
- Tausova, D., M. Dolejska, A. Cizek, L. Hanusova, J. Hrusakova, O. Svoboda, G. Camlik & I. Literak, 2012. Escherichia coli with extended-spectrum beta-lactamase and plasmid-mediated quinolone resistance genes in great cormorants and mallards in Central Europe. *Journal of Antimicrobial Chemotherapy* 6: 1103–1107.
- Thompson, R. C. A., 2004. The zoonotic significance and molecular epidemiology of *Giardia* and giardiasis. *Veterinary Parasitology* 126: 15–35.
- Travis, E. K., F. H. Vargas, J. Merkel, N. Gottdenker, R. E. Miller & P. G. Parker, 2006. Hematology, plasma chemistry, and serology of the flightless cormorant (*Phalacrocorax harrisi*) in the Galapagos Islands, Ecuador. *Journal of Wildlife Diseases* 42: 133–141.
- Trolliet, B., 1999. Great Cormorant (*Phalacrocorax carbo*) distribution and numbers in Europe. *Gibier Faune Sauvage* 16: 177–223.
- Usachev, E. V., M. I. Shchelkanov, I. T. Fediakina, D. N. L'vov, A. F. Dzharkeev, V. A. Aristova, A. I. Kovtunov, A. G. Prilipov, S. S. Iamnikova & D. K. L'vov, 2006. Molecular virological monitoring of Newcastle disease virus strains (Paramyxoviridae, Avulavirus) in the populations of wild birds in the Volga estuary (the 2001 data). *Voprosy Virusologii* 51: 32–38.
- van Eerden, M. R. & S. van Rijn, 1997. Population development of the great cormorant in Europe in relation to the question of damage to fisheries. In van Dam, C. & S. Asbirk (eds.), *Cormorants and Human Interests*. National Reference Centre for Nature Management, Wageningen: 34–44.
- van Eerden, M. R. & B. Voslamber, 1995. Mass fishing by cormorants at Lake IJsselmeer, the Netherlands: recent and successful adaptation to a turbid environment. *Ardea* 83: 199–212.

- van Eerden, M. R., S. van Rijn, S. Volponi, J.-Y. Paquet & D. Carss, 2012. Cormorant and the European Environment: Exploring Cormorant Ecology on a Continental Scale. COST Action 635 Final Report I: 126.
- van Eerden, M. R. & J. Gregersen, 1995. Long-term changes in the northwest European population of Cormorants *Phalacrocorax carbo sinensis*. *Ardea* 83: 61–79.
- van Roomen, M., E. van Winden & T. Langendoen, 2014. The assessment of trends and population sizes of a selection of waterbird species and populations from the coastal East Atlantic Flyway for Conservation Status Report 6 of The African Eurasian Waterbird Agreement. Wadden Sea Flyway Initiative, Wetlands International & Birdlife International.
- VanDijk, H. F. G., R. C. M. Creemers, J. P. L. Rijniers & J. G. M. Roelofs, 1989. Impact of artificial ammonium-enriched rainwater on soils and young coniferous trees in a greenhouse. *Environmental Pollution* 73: 317–336.
- Wetlands International, 2006. Waterbird POPULATION Estimates, Fourth Edition. Summary Report, 4th ed. Wetlands International, Wageningen.
- White, C. L., H. S. Ip, C. U. Meteyer, D. P. Walsh, J. S. Hall, M. Carstensen & P. C. Wolf, 2015. Spatial and temporal patterns of avian paramyxovirus-1 outbreaks in double-crested cormorants (*Phalacrocorax auritus*) in the USA. *Journal of Wildlife Diseases* 51: 101–112.
- White, C. R., D. Boertmann, D. Gremillet, P. J. Butler, J. A. Green & G. R. Martin, 2011. The relationship between sea surface temperature and population growth of Great Cormorants near Disco Bay, Greenland. *Ibis* 153: 170–174.
- Winney, B. J., C. D. Litton, D. T. Parkin & C. J. Feare, 2001. The subspecific origin of the inland breeding colonies of the cormorant *Phalacrocorax carbo* in Britain. *Heredity* 86: 45–53.
- Wiśniewska, H., S. Niewolak, E. Korzeniewska & Z. Filipkowska, 2007. *Enterobacteriaceae* family bacteria in a mesotrophic lake (Lake Długie Wigierskie) in the presence of Black cormorants. *Polish Journal Natural Sciences* 22: 486–499.
- Yesou, P. & P. Triplet, 2003. Taming the delta of the Senegal river, West Africa: effects on Longtailed and Great Cormorant *Phalacrocorax africanus*, *Phalacrocorax carbo lucidus* and Darter *Anhinga Melanogaster rufa*. *Vogelwelt* 124: 99–103.
- Zhang, W., J. Wan, K. Qian, X. Liu, Z. Xiao, J. Sun, Z. Zeng, Q. Wang, J. Zhang, G. Jiang, C. Nie, R. Jiang, C. Ding, R. Li, P. Horby & Z. Gao, 2014. Clinical characteristics of human infection with a novel avian-origin influenza A(H10N8) virus. *Chinese Medical Journal* 127: 3238–3242.
- Żółkoś, K. & W. Meissner, 2008. The effect of grey heron colony on the surrounding vegetation and the biometrical features of three undergrowth species. *Polish Journal of Ecology* 56: 65–74.