Impacts of nitrogen deposition to higher trophic levels in terrestrial ecosystems

Literature review

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Foreword

Excess atmospheric nitrogen (N) is a major pressure on biodiversity in the UK and globally. There is a wealth of evidence showing that nitrogen deposition is changing sensitive ecosystems, ranging from direct damage to plants to changes to the species composition and richness of entire ecosystems[1]. In England, 95.1% of sensitive habitats had background nitrogen deposition loading above the level considered to cause significant harmful effects[2]. Excess nitrogen results from human activity from both long distance and local sources such as agricultural activities (creating ammonia emissions) and road traffic. The mechanisms of impact are well recognised for higher and lower plants.

Over two thirds of wildflowers in England require low to medium levels of nitrogen, whilst less sensitive species such as nettles thrives in enriched soils[1]. Such effects of nitrogen on plant communities in turn affects dependent wildlife species. For example, negative impacts on butterfly species and other pollinators that are very sensitive to changes in their habitat are already being recorded[3]. There is evidence that nitrogen pollution has driven local extinctions of plant and lichen species across the UK, and increasing evidence of impacts to fungi, insects, birds, and other animals. All of these are important components of biodiversity and contribute to ecosystem functions such as soil formation, carbon sequestration and nutrient cycling.

Less is known regarding the sub-lethal and lethal impacts of gaseous air pollutants present in the air. Negative effects on vegetation occur via direct toxicity. For example, ammonia can be taken up through the leaves via stomata. Impacts include damage to the leaves and increased detrimental interactions with other abiotic and biotic stressors. Of the plant species, we know that mosses and lichens are most at risk from direct toxicity as they have limited detoxification capacity relative to their uptake potential and a large surface area relative to mass. The impact of Persistent, Bioaccumulative and Toxic substances (PBTs)[4] and Volatile Organic Compounds (VOCs) in the environment is a growing area of research, particularly in soils and human health respectively, however, much less is understood regarding the direct interaction with flora or fauna.

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[1] See https://www.plantlife.org.uk/application/files/1614/9086/5868/We_need_to_talk_Nitrogen_webpdf2.pdf

[2] Trends Report 2020 (https://uk-air.defra.gov.uk/library/reports?report_id=1001)

[3] Weiss, S. B. 1999. 'Cars, Cows, and Checkerspot Butterflies: Nitrogen Deposition and Management of Nutrient-Poor Grasslands for a Threatened Species'. Conservation Biology, 13: 1476-86

[4] The term persistent organic pollutant (POPs) is a more general term that includes persistent, bioaccumulative and toxic substances (PBTs).

In 2022, Natural England hosted two PhD student placements from the ACCE (Adapting to the Challenges of a Changing Environment) Doctoral Training Partnership culminating in two in-depth literature reviews of the existing and most up to date published research regarding the lethal, sub-lethal and habitat-mediated impacts of air pollutants (concentrations in the air and deposition to the ground) to higher trophic species. This focussed particularly on invertebrates. The reviews identify core evidence gaps and understudied research areas. These reviews will act as a critical first step in influencing wider future conservation policy and have significant impact on NE advise, raising public awareness of air quality as an environmental issue and engagement with NGOs.

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Executive summary

Report Purpose

There is evidence that nitrogen pollution has driven local extinctions of plant and lichen species across the UK, and increasing evidence of impacts on fungi, insects, birds, and other animals. All of these are important components of biodiversity and contribute to ecosystem functions such as soil formation, carbon sequestration and nutrient cycling.

In 2022, Natural England hosted two PhD student placements from the ACCE (Adapting to the Challenges of a Changing Environment) Doctoral Training Partnership culminating in two in-depth literature review of the existing and most up to date published research regarding the lethal, sub-lethal and habitat-mediated impacts of air pollutants (concentrations and deposition) to higher trophic species.

The aim of this rapid review is to investigate the impacts of nitrogen deposition on higher trophic levels in terrestrial ecosystems. This review will collate relevant experimental and field data from across the globe to bring together the existing evidence regarding nitrogen deposition impacts to British wildlife.

Key Points

Eutrophication

Most terrestrial and aquatic ecosystems are experiencing increased nutrient availability, which is affecting their structure and function. This literature review identified the following habitat-mediated impacts to higher trophic species.

- Changes in plant food quality – excess nitrogen alters nectar and pollen composition
- Changes in food abundance – nitrophilic plants outcompete nitrophobic plants causing changes in the abundance and composition of plant communities
- Changes to larval development – decreased temperatures at the soil surface caused by increasing plant height and density leads to slower growth and development of larvae
- Changes in plant chemistry – excess nitrogen changes the composition and concentrations of key amino acids in food plants

Critically, each of these changes will lead to impacts higher up the food chain. Whilst the existing research focusses heavily on invertebrates, this review identified several studies where higher trophic level impacts were identified. This is typically due to changes in the quality and/or quantity of the food source. The highest trophic level impacts from eutrophication found in this review were for raptors.

Acidification

Acidification causes a reduction in soil pH releasing potentially toxic heavy metals and reducing the availability of beneficial minerals. Acidification of soil is more likely to occur in poorly buffered soils such as heaths, forests and acidic grasslands. This literature review identified the following habitat-mediated impacts to higher trophic species.

- Acidification can reduce the amount of nectar produced by plants.
- Acidification is reported to be the main cause of reduced calcium concentrations in soil.
- Acidification reduces the pH of soils which can prevent certain food plants being able grow, even where conditions are otherwise optimal.

As is the case for eutrophication, impacts from acidification appear to be species specific, and specialists are more at risk than generalists. There appears to be more information about the impacts of eutrophication than impacts of acidification and the two are often reported together without distinction.

Conclusions and Recommendations

Specialist species depending on a limited number of food sources are at the greatest risk from impacts of both eutrophication and acidification. Very little research is available regarding the consequences of this for higher trophic species, particularly mammals. Whilst the evidence suggesting impacts to birds and raptors is growing, there is still a significant gap in the research to enable such claims to be made with confidence.

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Introduction

Nitrogen (N) deposition is considered one of the main threats to biodiversity (Klop *et al*., 2015; David *et al*., 2019). More than 60% of fixed N comes from anthropogenic sources (Stevens *et al*., 2018) and of this 80% originates from agriculture and 20% from combustion of fossil fuels from vehicle engines and industrial power plants (Stevens *et al*., 2018). Most studies investigating the impacts of N deposition have concentrated their efforts on vegetation, soil and water chemistry and ecosystem function (Nijssen *et al*., 2017).

The two main impacts of N deposition on terrestrial ecosystems are eutrophication and acidification (Stevens *et al*., 2018). Eutrophication is an increase in nutrients or minerals, N is a nutrient to most plant species and can be a limiting factor in the soil (Stevens *et al*., 2018). Excess N in the soil can cause several changes to plants such as increased biomass, altered plant communities, modified plant biochemistry and increased sensitivity to extreme weather conditions such as frost and drought (Stevens *et al*., 2018). Soil acidification can occur via two main methods, N can dissolve in rainwater to form nitric acid or combine with other chemicals and fall as 'acid rain' or N deposition can increase the concentration of H+ ions in the soil thereby reducing pH (Nijssen *et al*., 2017). The resulting acidification of the soil can change the availability of metals by increasing dissolved trace metals above their respective threshold for harm (Nijssen *et al*., 2017; Stevens *et al*., 2018). Experiments have been carried out internationally to investigate the impacts of eutrophication and acidification and also to try and reverse the effects of N deposition (Chen *et al*., 2009; Ormerod and Rundle, 1998; Vogels *et al*., 2021).

The aim of this rapid review is to investigate the impacts of N deposition on higher trophic levels in terrestrial ecosystems. This review will collate relevant experimental and field data from across the globe to bring together the existing evidence regarding N deposition impacts to British wildlife. The identification of "charismatic" or "flagship" species and wider impacts to ecosystem services will aid to develop a stronger narrative regarding the significance of air quality impacts to the environment. This review also aims to highlight gaps in the knowledge base and identify areas for future study.

Method

The search terms and exclusions were used specifically with the Web of Science core collection database (Table 1; Appendix 1). Results were sorted by relevance and only reviews and articles were selected. The first 100 results were downloaded and sorted by relevance from their title or abstract content. Where there were less than 50 relevant papers within the results the method was repeated until the number of relevant number of papers was more than 50. The findings of this review were based on these papers.

Table 1. Search terms and exclusions used for rapid review – see Appendix 1 for search string used.

Pollutant	Action	Habitat	Species	Exclusions
nitrogen OR nitrate OR "Nitrogen SAME deposition" OR eutrophication OR enrichment OR acidification OR "air quality" OR "air SAME pollut*	impact OR effect OR decline OR increase OR loss OR chang* OR pollution OR pollinat* OR abundance OR eutrophication OR enrichment OR insolation OR shading OR competition OR indirect OR acidification	flora OR soil OR fauna OR plants OR wildlife OR biodiversity OR habitat OR ecosystem OR ecolog* OR community OR population OR trophic	arthropod OR insect OR hexapod OR beetle OR parasit* OR invertebrate OR slug OR snail OR mollusc OR gastropod OR worm OR annelid OR millipede OR centipede OR chilopod OR myriapod OR arachnid OR spider OR pollinator OR wasp OR bee OR butterfl* OR moth OR fly OR flies vertebrate OR reptile OR bird OR mammal OR insectivo* OR passerine OR raptor	Sea, water, river, lake, human, adult, child, children, crab, lobster, bivalve, decapod, coral, marine, estuary

The search terms and exclusions resulted in 7,533 articles and 384 review articles. The first 100 results downloaded yielded 33 relevant and 67 irrelevant, the next 50 downloaded yielded nine relevant and 41 irrelevant, the final 100 downloaded yielded 12 relevant and 88 irrelevant. This gave a total of 54 papers to work from. After reading, 51 of the 54 papers fell within the scope of the review.

Eutrophication

Most terrestrial and aquatic ecosystems are experiencing increased nutrient availability, which is affecting their structure and function (Cross *et al*., 2007). Excessive soil enrichment with N can occur through fertiliser application, agricultural run-off and through atmospheric N deposition (David *et al*., 2019). N deposition can be mimicked experimentally using fertilisers containing N, such as ammonia (NH_3) or ammonium nitrate (NH_4NO_3) (Bobbink *et al*., 1998; Kurze *et al*., 2018).

Changes in Plant Communities – Food Quality and Quantity

Many animals feed on plants whether it be leaves, pollen, nectar, flowers, fruits, seeds or leaf litter (Nijssen *et al*., 2017). Some animal specialists feed only on specific plant species where others are generalists (David *et al*., 2019). Changes in plant communities can be observed as the number of different plant species, actual biomass or in the quality as a food source (Nijssen *et al*., 2017; Stevens *et al*., 2018; David *et al*., 2019). Excess N in the soil tends to favour fast-growing nitrophilic[5] plants, leading to taller homogenous vegetation that outcompetes the smaller slow-growing plants (David *et al*., 2019).

Impacts upon Invertebrates

The marsh fritillary (*Euphydryas aurinia*) is a monophagous[6] species of butterfly with a long larval stage and limited mobility (Brunbjerg *et al*., 2017). The presence of the preferred host plant devil's-bit (*Succisa parentsis*) determines the distribution of this butterfly species. In Denmark it was found that the absence of the host plant led to local extinction of this butterfly (Brunbjerg *et al*., 2017). The loss of the host plant was believed to be caused by eutrophication from direct fertilisation in Eastern Denmark as well as atmospheric deposition of N (Brunbjerg *et al*., 2017). A laboratory experiment in Germany found that increased N in host plants reduced larval survival rates in six different lepidopteran species by at least one third (Small heath (*Coenonympha pamphilus*), small copper *(Lycaena phlaeas*), sooty copper (*Lycaena tityrus*), speckled wood (*Pararge aegeria*), straw dot (*Rivula sericealis*) and blood-vein (*Timandra comae*); Kurze *et al*., 2018). Not all invertebrates suffer as a result of excess N in the soil; the peacock butterfly larvae (*Agalis io*) feed exclusively on nitrophilic[1] nettles (genus *Urtica*) that benefit from excess N in the soil (Habel *et al*., 2019). The nettles outcompete nitrophobic[7] plants creating an abundant supply of food for the peacock butterfly larvae (Habel *et al*., 2019). Another study found that both the peacock butterfly and the small tortoiseshell butterfly (*Agalis urticae*) have shorter larval periods, higher survival rates and heavier pupae when fed on nettles containing higher N concentrations (Kurze *et al*., 2017). However, insects displaying a positive relationship with increased plant N concentrations is not always good, especially if the species are considered pests.

[5] Preferring/thriving on soil rich in nitrogen (N)
[6] Feeds on only one type of food
[7] Not thriving in soil that is rich in nitrogen or nitrates

Increases in heather beetle (*Lochmaea suturalis*) numbers due to increased N concentrations can have devastating effects on heathland ecosystems (Bobbink *et al*., 1998; Stevens *et al*., 2018). Heather beetles have increased larval growth rates and increased adult sizes when feeding on heather (*Calluna vulgaris*) with higher concentrations of N (Bobbink *et al*., 1998). More frequent outbreaks of heather beetles in the Netherlands, thought to be caused by eutrophication, has led to the loss of large areas of heathland due to intensive insect herbivory (Bobbink *et al*., 1998). The reduction in the heather due to the heather beetles also increased light penetration down to the soil leading to the enhanced growth of understory grasses that outcompete the heather (Bobbink *et al*., 1998; Stevens *et al*., 2018).

Due to eutrophication an increase in plant height and density can prevent the sun's rays reaching the soil resulting in changes in humidity and reducing microclimate temperatures at the soil surface (Nijssen et al., 2017). This can impact the growth and development of larvae and eggs as the reduction in temperature slows down development. Invertebrates are ectothermic therefore rely on external heat sources for thermoregulation. If development takes longer this can misalign the timing of larval development and plant phenology[8] (Nijssen et al., 2017). For example, a reduction in numbers and local extinctions of the wall brown butterfly (*Lasiommata megera*) were found to be caused not only by the loss of host plants but more dramatically by microclimate cooling associated with excess N (Klop *et al*., 2015). Another study found a greater decline in egg-larva numbers than in pupa-adult numbers in hibernating species across Europe due to cooling microclimate in areas of high N deposition (Wallis de Vries and Van Swaay, 2006).

Equally important to wildlife is the quality of their food. An experimental study in Belgium found increased N deposition significantly altered the chemical and sugar composition of pollen and nectar of the flowering plant *S. parentsis* (Cleuemans *et al*., 2017). Treated plants were found to have higher concentrations of fructose and lower concentrations of glucose. Amino acid concentrations and compositions were also found to be significantly different (Cleuemans *et al*., 2017). As part of this experiment bumblebees (*Bombus terrestris*) fed on treated or untreated plants. More dead larvae and fewer workers were found in bumblebee hives fed on treated plants (Cleuemans *et al*., 2017). A second experimental study on bumblebees found they preferentially sought out the nectar from treated plants (increased N) even though this reduced their survival by 22% (Hoover *et al*., 2012). Changes in the composition of sugars in nectar due to N deposition can also impact insect assemblages as some pollinators have species or sex specific preferences and requirements of nectar (David *et al*., 2019). For example, Diptera were found to prefer to visit plants with lower sucrose nectar content whereas Lepidoptera prefer higher sucrose content nectar (Petanidou, 2005). It was also found that female Adonis blue butterfly

[8] Plant life cycle

(*Lysandra bellargus*) prefer high glucose nectars, in contrast to males which preferred high sucrose nectars (Rusterholtz and Erdhardt, 2000).

It should be noted that several experimental studies have found no significant effects of N deposition on arthropod communities (Burke *et al*., 2010; Fountain *et al.,* 2008). One study has suggested that the application of N in the form of a fertiliser could be beneficial to biodiversity (Rowe *et al*., 2006). The literature indicates that there can be positive and negative effects of N deposition on arthropod communities, but these effects are species specific and specialists are more likely to be impacted than generalists.

Changes in Plant Chemistry – Amino Acid Composition and Concentration

The previous section looked at the quality of plants as food in terms of N concentration and its influence upon pollen or nectar chemical composition. Equally important is the composition and concentrations of amino acids in the plants animals consume (Stevens *et al.,* 2012; David *et al*., 2019). N deposition has been found to change both the concentrations and composition of amino acids in plants (Cleuemans *et al*., 2017) as plants try to deal with excess N by producing more amino acids that have a higher N content (Siepel *et al*., 2009). Some essential amino acids cannot be synthesised or be synthesised fast enough by animals to meet biological demands, therefore must be supplemented in the diet (Siepel *et* al., 2009; Kraus *et al*., 2019). Amino acids have many biological functions such as cell structure, enzymes, transport, storage and receptor molecules to name a few (Kraus *et al*., 2019).

Impacts upon Invertebrates

Generally, N addition appears to increase amino acid concentrations, most commonly asparagine and glutamine (Cleuemans *et al.,* 2017; David *et al*., 2019). High concentrations of specific amino acids have different affects, for example increased concentrations of β-alanine has been shown to reduce motor skills in foraging bees (David *et al*., 2019). Increased concentrations of proline can be useful for the conversion of energy as it can be metabolised quickly which is ideal for initiating flight in insects (Carter *et al*., 2006). Proline can also be an attractant, but only at moderate concentrations; too high a concentration and bees have been shown to lose interest in the nectar (Carter *et al*., 2006). Gamma-aminobutyric acid (GABA) can stimulate feeding in adult insects however can be lethal to larvae at high concentrations (Nepi, 2014). There is also some evidence that a reduction in some amino acids can impact chemosensory cells which could impact foraging choices (David *et al*., 2019). A study in the Netherlands found that changes in amino acids in the leaves of the oak (*Quercus* sp.) lead to a reduction in moth caterpillar numbers. The study also suggested that this may have impacted the amino acid content of the surviving caterpillars which are a food source for higher trophic species (Siepel *et al*., 2009; Nijssen *et al*., 2017).

Higher Trophic Level Impacts

To survive, an adequate food source is required and the adequacy of a food source can be measured by quality and quantity. A scarcity of food or a reduction in food portions could lead to an energy imbalance as more energy is expended foraging, catching and digesting prey relative to the energy content of the prey item itself (Siepel *et al*., 2009).

In the Netherlands heathland black grouse (*Lyrurus tetrix*) numbers have declined due to a high mortality rate in chicks and there is some indication that this is due to a reduction in the mean size of invertebrate prey items available (Siepel *et al*., 2009). A study also in the Netherlands found that as N concentrations in grasslands increased the mean size of invertebrates decreased (Siepel, 1990). In this study the reduction in invertebrate size was not compensated for by an increase in invertebrate biomass as indicated in other studies (Haddad *et al*., 2000; Siepel *et al*., 2009). Consequently, it has been suggested that the cause of the decline in black grouse may be associated with increased N concentrations. In the study (Siepel *et al*., 2009) it was indicated that the black grouse was not the only heathland species negatively impacted by the reduction of mean prey size as there are several other reliant species including; red-backed shrike (*Lanius collurio*), great grey shrike (*L. excubitor*), northern wheatear (*Oenanthe oenanthe*), Cuckoo (*Cuculus canorus*) and the sand lizard (*Lacerta agilis*). A study on the Dutch costal dunes also found that a reduction in mean prey size negatively impacted bird numbers and even caused local extinctions (Kuper *et al*., 2000).

Field studies in the Netherlands investigating the decline in Sparrowhawk (*Accipiter nisus*) numbers (Siepel *et al*., 2009; Nijssen *et al*., 2017; Van den Burg, 2018) demonstrated this to be due to abnormalities in egg development and reduced breeding success (Siepel *et al*., 2009; Van de Burg, 2018). A decline in sparrowhawk breeding pairs was found in mineral poor forests (Siepel *et al*., 2009), and of the breeding pairs that did exist in mineral poor forests up to a 50% pectoral muscle reduction was identified during the breeding season (Siepel *et al*., 2009). The pectoral muscles of female sparrowhawks are important not only for flight to hunt and forage but they are also important for brooding eggs (Siepel *et al*., 2009). The abnormalities in the sparrowhawk eggs were due to vitamin B2 deficiencies (Siepel *et al*., 2009; Van de Burg, 2018). Analysis revealed the vitamin B2 deficiency in the eggs were based upon an amino acid deficiency lag, the vitamin present in the egg can only be utilised if the correct amino acids are present (Siepel *et al*., 2009; Van de Burg, 2018). It was hypothesised that the reduction in the female sparrowhawk pectoral muscle mass was to compensate the misalignment of amino acids required by the eggs and the dietary amino acids that were lacking in the sparrowhawks prey (Siepel *et al*., 2009). It was suggested that the required amino acids were lost in the food chain from oak to caterpillar and moth to great tit (*Parus major*) ending with the sparrowhawk (Siepel *et al*., 2009). The embryo losses found in the sparrowhawks were also the same as those found in domestic fowl suffering from a similar dietary amino acid imbalance (Van den Burg, 2018). It has been suggested that increased N deposition could therefore be contributing to the decline of this predatory bird species and more research is needed to determine how these deficiencies occur in wild bird populations.

Changes in plant communities have also been found to negatively impact some bird species, a study again from the Netherlands indicated that an increase in grass coverage led to a decline in ants which in turn led to a decline in the green woodpecker (*Picus viridis*) (Van Tol *et al*., 1998). One study from the United States indicated a population decline in the northern-flying squirrel (*Glaucomys sabrinus*) may be linked to N deposition due to the loss of nitrophobic[3] lichens which comprise the bulk of the flying squirrels winter diet (Clark *et al*., 2017). This again highlights how specialist feeders are at higher risk.

In general, there appear to be very few studies investigating the impacts of eutrophication on higher trophic levels. Most notably, the studies that were available in this rapid review were all from the Netherlands. Surprisingly, there appears to be very little available on the impacts of eutrophication on herbivorous mammals and nothing on insectivorous mammals.

Acidification

Acidification causes a reduction in soil pH releasing potentially toxic heavy metals and reducing the availability of beneficial minerals (David *et al*., 2019). Acidification of the soil is more likely to occur in poorly buffered soils such as heaths, forests and acidic grasslands (David *et al*., 2019). Acidification, like eutrophication, can alter plant species richness by reducing the numbers of plants sensitive to low pH and heavy metals (David *et al*., 2019). Acidification and eutrophication from N deposition appear to often be reported concurrently making the individual impacts hard to tease apart (Bobbkin *et al*., 2003; Stevens *et al*, 2018; David *et al*., 2019). However, eutrophication through atmospheric N deposition appears to have a more far-reaching impact than acidification (Van Tol *et al*., 1998).

Impacts upon Invertebrates

A study investigating acidic grasslands across the UK found that N deposition to the acidic topsoil resulted in a reduction in flowering plants generally visited by large-bodied bees but had no impact on generalist plants visited by smaller bees (Stevens *et al*., 2018). The study also found a reduction in nectar production in areas of high N deposition (Stevens *et al*., 2018). It stands to reason that like eutrophication, acidification has a greater impact on specialists rather than generalists. Similarly, as discussed earlier, the absence of the host plant devil's-bit (*Succisa parentsis*) preferred by the marsh fritillary (*Euphydryas aurinia*) led to the local extinction of this butterfly in some areas of Eastern Denmark (Brunbjerg *et al*., 2017). The cause of the decline of this plant in these areas was due to eutrophication. Interestingly, the same study found that in Western Denmark the soil had the low nutrient levels favourable to devil's-bit but a reduced pH (Brunbjerg *et al*., 2017). They concluded that a loss of the host plants in areas of Western Denmark and local extinction of the marsh fritillary was due to acidification rather than eutrophication (Brunbjerg *et al*., 2017).

A long-term study site in Alberta, Canada looked at the effects of acidification on biodiversity along an acidification gradient from a sour gas processing plant (Cárcamo and Parkinson, 2001). Although this study concentrates on the effects of sulphur dioxide, the effects measured could mirror the acidifying effects of N deposition. High contamination and subsequent acidification showed a significant reduction in numbers of earthworms, snails, ants and some carabid beetle species when compared to less contaminated sites (Cárcamo and Parkinson, 2001). In the most contaminated site over the two seasons of data collection no snails were found and only two earthworms were found in the first year followed by zero in the second year (Cárcamo and Parkinson, 2001). The absence of snails at highly acidified sites occurs as their calciferous shells disintegrate at low pHs (Cárcamo and Parkinson, 2001). Calcium availability is known to impact snail distribution, for example this study found that the most contaminated site had the lowest calcium concentration (Cárcamo and Parkinson, 2001). It has been established that soil calcium concentrations have a larger impact on snail numbers than soil pH, however the chief cause of reduced calcium concentrations in soil is atmospheric deposition of acidifying compounds such as SO_2, NO_x and NH_3 (Graveland and Van der Wal, 1996). Not all carabid beetle species in the study were vulnerable to the acidified conditions, some species maintained healthy populations along the acidification gradient and other species thrived at a lower pH (Cárcamo and Parkinson, 2001). Overall, the authors concluded that ecological specialists were more vulnerable to acidification than generalists (Cárcamo and Parkinson, 2001).

Higher Trophic Level Impacts

Studies across Europe have found that some forest dwelling passerine birds have low reproductive success and egg defects (Graveland and Van der Wal, 1996). Great tits (*Parus major*) in the Netherlands produced eggs with thin, porous shells and tended to desert their clutches. The cause of the eggshell defects and associated reduced reproductive success was due to calcium deficiencies (Graveland *et al*., 1994). Birds do not store enough calcium for egg laying, therefore reproducing females must supplement their diet with calcium rich food sources (Graveland *et al*., 1994). In forests with successfully reproducing tits (*Parus* sp.), snails were used as a calcium source. Great tits that had egg defects also collected calcium from anthropogenic sources such as mortar or chicken eggshells from outside the forest (Graveland and Van der Wal, 1996). The birds with eggshell defects were found in forests with a reduced availability of snails and this was due to low concentrations of calcium in the soil and leaf litter (Graveland *et al*., 1994; Graveland and Van der Wal, 1996). As discussed, a key cause of reduced calcium concentration in soil is due to atmospheric deposition of acidifying compounds (Graveland and Van der Wal, 1996). This suggests that one of the causes of reduced passerine bird numbers could be attributed to N deposition.

Conclusion

The aim of this rapid review was to investigate the impacts of N deposition on higher trophic species in Britain. Due to time constraints the focus was on breadth rather than depth of information. Few studies from the rapid review were carried out in the UK however inferences can be made from the European species and habitats investigated.

The majority of the literature from this rapid review concentrated on eutrophication and insects, with more studies from the Netherlands than any other country. Whilst there were not many UK studies, this could be due to the time constraints and restricted scale of the review. The main message from the literature appeared to be that specialists are at a much higher risk than generalists and the impacts of N deposition are species specific. There appears to be very little literature available investigating the effects of N deposition on higher trophic levels. The highest trophic levels found with potential impacts from acidification and eutrophication were birds (raptors and passerines respectively). There appears to be very little in the literature about mammals, one mention of herbivorous mammals was found yet there was nothing on insectivores, omnivores or carnivores. It is not a great leap to think that losses in insect communities would impact insectivorous mammals in the same way it has impacted birds.

This review did find evidence of N deposition contributing to the decline of bird species common to the UK. Although, this area would benefit from a great deal more research. N deposition evidently could have negative impacts on higher trophic levels which strengthens the case for reducing anthropogenic sources of N. Public awareness is vital as it is only through collective action and demand for change the necessary progress can be made.

If all anthropogenic N deposition stopped tomorrow the recovery time for some habitats could be decades. One experiment found that plant communities retained their enriched soil state for over 20 years (David *et al*., 2019). Also there appeared to be a lag between plant and higher trophic levels, such as insects, re-establishing to pre-N deposition "norms" (David *et al*., 2019). However, in acidified forests liming over a four-year period increased soil calcium concentrations and the number of snails increased to become comparable to forests with non-acidic soil (Graveland and Van der Wal, 1996). Although in some cases it may be slow there is the opportunity for recovery.

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Appendix

(1) Search string

((((((((((((((ALL=(nitrogen OR nitrate OR "Nitrogen SAME deposition" OR eutrophication OR enrichment OR acidification OR "air quality" OR "air SAME pollut*")) AND ALL=(impact OR effect OR decline OR increase OR loss OR chang* OR pollution OR pollinat* OR abundance OR eutrophication OR enrichment OR insolation OR shading OR competition

OR indirect OR acidification)) AND ALL=(flora OR soil OR fauna OR plants OR wildlife OR biodiversity OR habitat OR ecosystem OR ecolog* OR community OR population OR trophic)) AND ALL=(arthropod OR insect OR hexapod OR beetle OR parasit* OR invertebrate OR slug OR snail OR mollusc OR gastropod OR worm OR annelid OR millipede OR centipede OR chilopod OR myriapod OR arachnid OR spider OR pollinator OR wasp OR bee OR butterfl* OR moth OR fly OR flies vertebrate OR reptile OR bird OR mammal OR insectivo* OR passerine OR raptor)) NOT ALL=(sea)) NOT ALL=(water)) NOT ALL=(river)) NOT ALL=(lake)) NOT ALL=(human)) NOT ALL=(adult)) NOT ALL=(child)) NOT ALL=(children)) NOT ALL=(crab)) NOT ALL=(lobster)) NOT ALL=(bivalve)) NOT ALL=(decapod)) NOT ALL=(coral) NOT ALL=(marine) NOT ALL=(estuar*).

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