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Review

Liming impacts on soils, crops and biodiversity in the UK: A review

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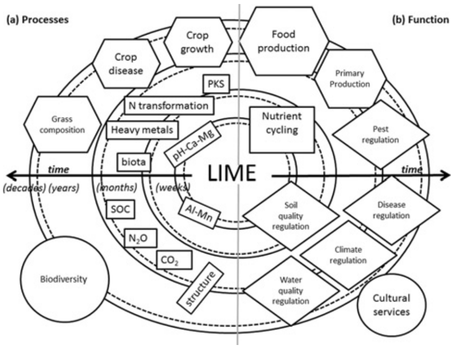
HIGHLIGHTS

- Liming has numerous far reaching impacts on soil and plant processes and function.
- Liming impacts on soils are positive such as increased nutrients and biota.
- Liming crops and grassland is beneficial to yield and quality and for grazing stock.
- Liming impacts on biodiversity vary significantly with evidence of positive effects.
- A qualitative framework shows how liming impacts change with time.

GRAPHICAL ABSTRACT



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ABSTRACT

Fertile soil is fundamental to our ability to achieve food security, but problems with soil degradation (such as acidification) are exacerbated by poor management. Consequently, there is a need to better understand management approaches that deliver multiple ecosystem services from agricultural land. There is global interest in sustainable soil management including the re-evaluation of existing management practices. Liming is a long established practice to ameliorate acidic soils and many liming-induced changes are well understood. For instance, short-term liming impacts are detected on soil biota and in soil biological processes (such as in N cycling where liming can increase N availability for plant uptake). The impacts of liming on soil carbon storage are variable and strongly relate to soil type, land use, climate and multiple management factors. Liming influences all elements in soils and as such there are numerous simultaneous changes to soil processes which in turn affect the plant nutrient uptake; two examples of positive impact for crops are increased P availability and decreased uptake of toxic heavy metals. Soil physical conditions are at least maintained or improved by liming, but the time taken to detect change varies significantly. Arable crops differ in their sensitivity to soil pH and for most crops there is a positive yield response. Liming also introduces implications for the development of different crop diseases and liming management is adjusted according to crop type within a given rotation. Repeated lime applications tend to improve grassland biomass production, although grassland response is variable and indirect as it relates to changes in nutrient availability. Other indicators of liming response in grassland are detected in mineral content and herbage quality which have implications for livestock-based production systems. Ecological studies have shown positive impacts of liming on biodiversity; such as increased earthworm abundance that provides habitat for wading birds in upland grasslands. Finally, understanding of liming impacts on soil and crop processes are explored together with functional aspects (in terms of ecosystems services) in a new qualitative

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framework that includes consideration of how liming impacts change with time. This holistic approach provides insights into the far-reaching impacts that liming has on ecosystems and the potential for liming to enhance the multiple benefits from agriculturally managed land. Recommendations are given for future research on the impact of liming and the implications for ecosystem services.

Contents

1. Introduction

Healthy and fertile soil is fundamental to our ability to achieve food security and agricultural sustainability, but is challenged due to poor management and environmental change. Increasingly soils are being degraded and becoming marginal for production. Recent concerns about global drivers of soil degradation include salinization, erosion (wind and water-borne) and acidification and contamination (FAO, 2015). The situation is made more difficult by the need to increase food production to feed an increasing global population. Consequently, there is global interest in the development and implementation of sustainable agricultural practices. Practices need to maintain soils' ability to produce food while also delivering other key ecosystem services such as the regulation and storage of nutrients and C in soils.

The benefits of applying limestone to ameliorate acidic soils have been known for centuries. For instance, the use of marl and burnt lime was a central part of the land improvement system that was developed during the eighteenth century in Berwickshire, Scotland (Dodgshon, 1978). Agriculture continues to develop and change and the focus now lies not solely on production, but also on maintaining a healthy environment. Thus, today the challenge for liming (and other farm practices) is to achieve sustainable management in a whole system approach (Gibbons et al., 2014). The impact of liming is far-reaching and while previous research on liming has strongly focused on individual components of soil processes or on single crops, there is an urgent need to better understand the broader impacts of liming.

The primary management 'problem' that liming addresses is soil acidification. Acidification is caused both by natural processes (via C, N and S cycling) and anthropogenic activities. Acid deposition threatens ecosystem health (especially water quality) and liming has had an important mitigation role (Clair and Hindar, 2005). Recently, sulphur deposition has decreased across the UK and thus the acidic load has declined appreciably (Kirk et al., 2010). Another cause of acidification is the application of nitrogen fertilisers. There are global concerns regarding acidified arable land, particularly in China, where it is a major challenge (Guo et al., 2010). Therefore, questions are being asked about the potential mitigation value of lime. The impacts of liming on greenhouse gas emissions are complex and there are markedly different potential changes in emissions between different gases. A recent comprehensive review reports on this further (Kunhikrishnan et al., 2016), but briefly some examples include: decreased nitrification-induced nitrous oxide (N_2O) production, increased methane (CH_4) oxidation, and depending on the antecedent soil pH, liming material can act either as a net source or a net sink for carbon dioxide (CO_2).

From an agricultural perspective the principal driver for lime application is soil pH. A recent report indicates that >40% of arable soils in the UK have a soil pH <6.5 and 56% of grassland soils have a pH <6.0 (PAAG, 2015) (Fig. 1). The Professional Agricultural Analysis Group (PAAG) report is based on the collation >170,000 soil analyses (pH, P, K, Mg) from across the UK. These results indicate significant differences in soil pH across the UK reflecting differences in soil types and dominant land (crop) uses in different regions. Fig. 1 shows that >60% of samples from Wales and Scotland had soil pH <6 compared with 1% in East Anglia. This suggests there are significant areas where lime application would be recommended based upon good practice in England and Wales (DEFRA, 2010) and in Scotland (Sinclair et al., 2014). The reports

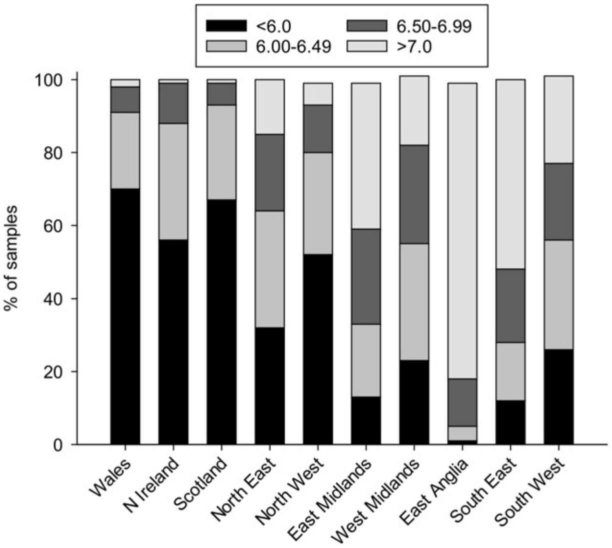

Fig. 1. A summary of the soil pH classes of agricultural land in different regions of the UK in the 2014/15 season.
Source: (PAAG, 2015); based on >170,000 soil samples.

from earlier studies are different. Oliver et al. (2006) reported that soil pH had changed little between 1971 and 2001, while a separate analysis of the 1978 to 2003 period found that soil pH had increased (Kirk et al., 2010). These studies (Oliver et al., 2006 and Kirk et al., 2010) provide an interesting historical perspective at a large scale, but do not represent an up-to-date evaluation of soil pH status in the UK. Moreover because there are parts of the UK with a large percentage of acidic soils (Fig. 1), it is now important to review the impacts of liming.

The UK government abolished a lime subsidy in 1977/78 (MAFF, 1979) and lime applications have declined since then. In recent years the production of agricultural lime has also declined in the UK (Fig. 2). During the 1980s and early 1990s between 3-4,000,000 tonnes of lime was produced annually, but over the last 10 years production has often been <2,000,000 tonnes. Current limestone production for agriculture is much less than the average estimated annual lime loss for the UK (4,250,000 t $CaCO_3$) (Goulding and Annis, 1998). The trend shown in Fig. 2 agrees with the British Survey of Fertiliser Practice which records the percentage of fields that farmers have applied limestone (DEFRA, 2016). Overall, there has been a general decline in liming. The mean area of agricultural land limed for the 10 years prior to 2016 was: 8.6% for arable crops, 6.1% for temporary grassland (<5 years) and 3.2% for permanent grassland (>5 years) (DEFRA, 2016). These statistics suggest that liming is becoming less common and the implications of this decline in liming need to be understood.

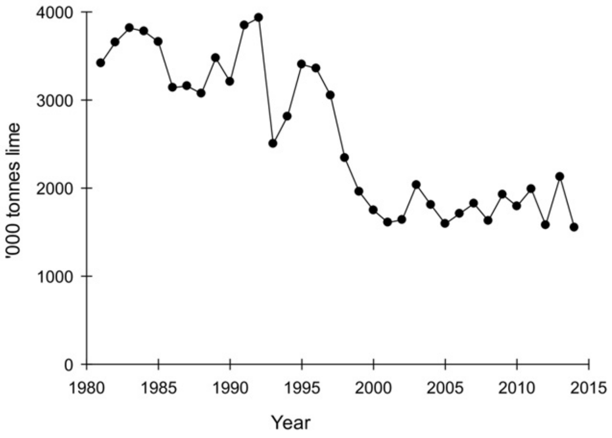

Fig. 2. Production of limestone, dolomite and chalk for agricultural uses (thousand tonnes) in Great Britain from 1981–2014.
Source: (Idoine et al., 2016).

Many of the benefits of liming are well known and these include increased availability of nutrients for crops. The positive impact which liming has on grain and biomass yield of arable and grassland crops is significant for food security (Goulding, 2016), however the liming effects on crop quality and crop disease status also require attention. Liming benefit varies between crops, and differential impacts on major commercial crops need to be re-evaluated in the light of recent changes in crop rotation and the overall decline in lime usage (Figs. 1 and 2) (DEFRA, 2016). There are also drawbacks to liming and some negative impacts. Gibbons et al. (2014) state the net climate change impact of liming is negative because of the CO_2 emissions produced as acidity is neutralized. Despite the volume of research which exists on liming there remain knowledge gaps; for example, the liming impacts on soil carbon stocks (Paradelo et al., 2015), greenhouse gas emissions (Kunhikrishnan et al., 2016) and soil phosphorus uptake (Barrow, 2017). It is not enough to focus on soil impacts alone; a comprehensive consideration must also be given to crops (plants) and biodiversity too.

This review assesses the impacts of liming agricultural land, with a specific focus on UK studies. In this context we define agricultural land as including arable and permanent grassland, but excluding land used for rough grazing and forestry. The review: (1) evaluates the key factors which influence lime management practices at a farm level; (2) critically evaluates the response of some important soil processes that are impacted by liming with subsequent implications for soil function; (3) assesses the impact of liming on crops (arable and grassland) in terms of yield and quality; (4) assesses the impacts of liming on biodiversity including a consideration of botanical richness and broader ecosystem effects such as impacts on bird species; (5) explores the liming impacts of multiple processes using a new qualitative framework which also accounts for the functional aspect of soils, crops and biodiversity. Finally, this review also (6) describes key outcomes and suggests areas of uncertainty for liming impacts and proposes important areas for future research on liming impacts.

2. Key factors which influence liming management

The management of lime is complex, because of the large differences in land use and the potential different management objectives for a given parcel of land. Three fundamental factors that directly influence liming management are discussed below.

2.1. Lime material type and quality for liming management

The British Survey of Fertiliser Practice (2015) reports that the most common liming material for arable crops and grassland is ground limestone ($CaCO_3$) (DEFRA, 2016). The second most applied material is dolomitic limestone ($CaMg(CO_3)_2$) and there are several minor liming materials including slaked lime($Ca(OH)_2$), pelletized materials (finely ground granules) (Higgins et al., 2012), natural shell sands and burnt lime (CaO). Other alternative liming materials include industrial gypsum-like by-products (Garrido et al., 2003). There is also some liming value in various composts and digestate materials and consequently for some bulky organic fertilisers there is no need to lime (Sinclair et al., 2013). For all materials with liming value, two important quality characteristics are: (*i*) the neutralising value (NV) and (*ii*) the particle size. In the UK, regulations require that those who sell limestone must describe their product in terms of the NV and the percentage by weight that passes through a 150 micron sieve. The NV is the amount of acidity that a liming material will neutralise and it is expressed in comparison with pure CaO. Studies evaluating limestone particle size show that the finest material is best for increasing soil pH and reducing the concentration of exchangeable Al (Álvarez et al., 2009). On lime type Conyers et al. (1996) developed a predictive model of 12 different liming materials to determine their total efficiency and significant differences were found which showed that the calcitic limestones performed better (due to higher solubility) than the dolomite limestones. Furthermore, the cations from calcitic limestones will support better aggregation than magnesium-rich liming materials (Vance et al., 2002). Bailey et al. (1989b), in an earlier a predictive model of 34 different liming materials, found that their effective CaO content (ECC) increased as the content of fine particles (<150 μm) increased and decreased as the content of coarse particles (>2.36 mm) and $MgCO_3$ contents increased. The chemical composition of limestone therefore is an important consideration.

2.2. Lime application method and tillage for liming management

The method of applying lime is an important practical issue that has implications for the effectiveness of liming. Methods for applying lime depend on the type of land use e.g. for arable crops lime can be either top-dressed or incorporated when ploughing. For permanent grassland where the soil is not disturbed there are fewer options. Pelletized lime is very convenient form of lime which can be spread accurately and evenly using conventional fertilizer-spreading equipment (Higgins et al., 2012). In addition, a reduced amount needs to be applied with pelletized lime. The amount and timing of lime applications are other factors which can be modified. Álvarez et al. (2009) showed that a single application was more effective than three annual split doses. The effectiveness of lime varies according to tillage practice and a lack of tillage (lime incorporation) influences the lime effectiveness. Therefore, in no tillage or direct drilling systems, a higher rate of lime should be applied compared to situations in which lime is incorporated by tillage. Secondly, lime should be applied earlier to no tilled land than for soil under conventional tillage practices (Conyers et al., 2003). These measures are suggested to drive the leaching of bicarbonate and so that the lime movement precedes excessive exchangeable Al.

2.3. Soil properties and their influence on liming management

Soil buffering capacity influences the extent to which a soil is able to resist changes in ion concentration in the solution phase. Soil pH is the simplest indicator to determine the need for lime, while soil texture and organic matter content are two other soil properties which directly influence the lime requirement. To illustrate this point, the lime requirement across a wide range of soil pH values for four different soil classes are shown for soils in Scotland, UK (Fig. 3) (Sinclair et al., 2014). For mineral soils, the percentage of sand reduces both the lime requirement and the initial soil pH at which lime is required. The other mineral class includes soil with higher clay content and these have the greatest lime requirement. In comparison, higher organic matter levels reduce lime requirement and thus humose soils require less lime than the other mineral soils. Bailey et al. (1989a), working with widely varying organic matter soils in Northern Ireland, developed a method for predicting lime requirement based solely on soil pH and organic matter content. Their results demonstrated that soil titratable acidity was primarily related to soil organic matter content.

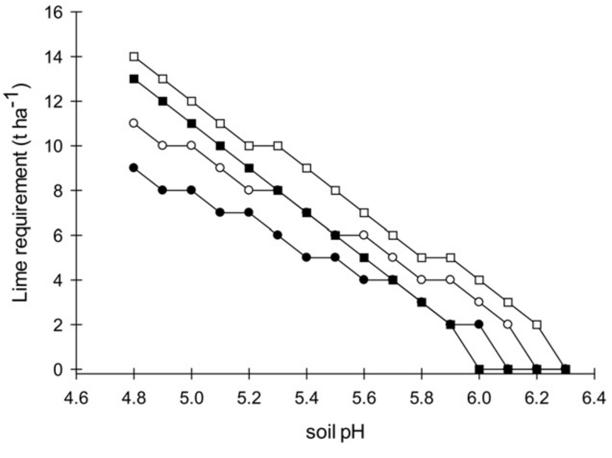

Fig. 3. The effect of soil pH on lime requirement (t/ha) for four arable soils according to different soil classes (● = sand, ○ = sandy loam, ■ = humose, □ = other mineral) used in Scotland, UK (Sinclair et al., 2014).

For grassland the liming recommendations in England and Wales (RB209) indicate that a positive response to lime can be found up to a pH 6 (1 soil: 2.5 water) for mineral soils and pH 5.3 for peaty soils (DEFRA, 2010). Apart from pH, other soil properties such as the cation exchange capacity (Lemire et al., 2006), Fe and Al content (Curtin and Trolove, 2013) have also been shown to influence lime requirement; while some soil properties such as soil moisture and temperature influence the reaction rate of lime (Fageria and Baligar, 2008). Despite the potential complexity of how soil properties influence lime requirement the RothLime model (Goulding et al., 1989) has proven to be both simple (only two inputs: soil pH and soil texture) and yet achieves very acceptable predictions. Further discussion is given below (Section 3) on liming-induced changes of soil processes which is evidence of the complexity of soil responses and emphasises the importance of understanding the management of limed soil.

3. The impacts of liming on soil processes

3.1. Liming impacts on neutralising acidity

The application of liming materials changes the soil chemical balance. Liming materials contain Ca^{2+} or Mg^{2+} cations (sometimes both) and their supply has a neutralizing effect displacing the H^+ in the soil solution. For limestone the reaction is described as:

$$CaCO_3 + 2H^+ = Ca^{2+} + CO_2 + H_2O \tag{1}$$

For dolomite the reaction is:

$$CaMg(CO_3)_2 + 2H^+ = 2HCO_3{}^- + Ca^{2+}Mg^{2+} \tag{2}$$

$$2HCO_3{}^- + 2H^+ = 2CO_2 + 2H_2O \tag{3}$$

For calcium silicate the reaction is:

$$CaH_2SiO_4 + 2H^+ = Ca^{2+} + H_4SiO_4 \tag{4}$$

The equations above describe some of the neutralisation processes that result from liming. The reaction of Ca^{2+} or Mg^{2+} with H^+ can form $CO_2 + H_2O$ and this leads to an increase in pH. For each liming material given here, there are 2 moles of acid that are consumed. In the case of limestone and dolomite there is liberation of the greenhouse gas CO_2 (Eq. (3) shows the dissolution of CO_2) which indicates that liming impacts the carbon cycle. Thus, the neutralisation of acidity by liming has significant implications for the biogeochemical cycling of C, N and S (Helyar, 1976) and the changes in the levels and chemical forms of these elements is fundamental to many agricultural and land-use activities.

3.2. Liming impacts on soil biota and biological processes

Liming, whether applied to arable or grassland systems has been shown to have impacts on both the abundance and community composition of almost all types of soil organism including bacteria, fungi, archaea, nematodes, earthworms, and microarthropods. Table 1 provides selected examples of how liming impacts specific soil biota, with associated soil processes given and a link to the impact on function. There is well established research to demonstrate that liming soils

Table 1
The impacts of liming on soil biota and the associated soil biological processes and their function.

Organism	Organism change	Associated process	Overall ES impacts	Reference
Bacteria	↑ Abundance	Decomposition	+ve (nutrient cycling)	(Bothe, 2015) (Millard and Singh, 2010)
Rhizobia	Composition change	Nutrient delivery	+ve (nutrient cycling)	(Zhalnina et al., 2013b) (Durán et al., 2013)
Fungi	↓ Abundance	Recalcitrant decomposition	+ve (C storage)	(Bothe, 2015) (Millard and Singh, 2010)
AM fungi	1. ↑ Abundance to pH 5–6, but ↓ if pH >7 2. Composition change	Nutrient delivery, soil aggregation, antagonist defence	Variable	1. (Castillo et al., 2014; Johnson et al., 2005; Sano et al., 2002; Takács et al., 2006) 2. (Gomes et al., 2015) (Clark, 1997)
Pathogens	↓ Abundance	Disease	+ve (disease regulation)	(Donald and Porter, 2009) (Provance-Bowley et al., 2010) (Buerkert and Marschner, 1992)
Nematodes	1. ↑ Abundance? 2. Composition change?	Disease, decomposition, predation	−ve (disease regulation)	1. (Van der Wal et al., 2009) 2. (Murray et al., 2006)
Earthworms	↑ Abundance	Decomposition, soil aggregation	+ve (nutrient cycling)	(McCallum et al., 2016)
Microarthropods	No effects	Decomposition	Variable	(Van der Wal et al., 2009)

↑ = increase; ↓ = decrease; +ve = positive; −ve = negative.

increases the bacterial to fungal ratio of soils (Bothe, 2015), and a shift to a soil pH above 5 has impacts on decomposition rates as demonstrated by changes in soil respiration (Bardgett and Leemans, 1995; Bardgett et al., 1996). This shift in abundance is correlated with changes in community composition of both general bacterial and fungal communities (Ai et al., 2015; Cassman et al., 2016; Zhao et al., 2015). These changes in abundance have been shown to increase the proportion of the bacterial (particularly gram-negative) communities (Treonis et al., 2004), as well as the fungal and archaeal communities accessing root exudated carbon (Dawson et al., 2003; Ignacio Rangel-Castro et al., 2005). In addition, reductions in the proportion of fungi have been linked to reductions in aggregate stability (and thus general soil stability) (Karki and Goodman, 2011), but greater proportional incorporation of carbon into fungal structures (Tavi et al., 2013). Changes in bacterial community composition have been shown to influence the nitrogen cycling potential of soils (Gray et al., 2003; Wakelin et al., 2009), and chitinase activity (Krsek and Wellington, 2001). Other beneficial impacts have been reported after liming, e.g. Roper (2005) found that wax-degrading bacteria were significantly increased and in turn had impacts on soil wettability which has implications on water infiltration. Studies on archaea are rarer, but they also appear to experience a shift in community composition towards ammonia-oxidizing archaea (Zhalnina et al., 2013b), which may be more of a response of the archaea to nitrogen inputs than liming itself. Thus liming can have strong impacts on the microbial component of soils (see further discussion below on soil N processes).

Within the broad category of bacteria and fungi there has been significant interest in the influence of liming on two groups: beneficials (such as rhizobia and arbuscular mycorrhizal (AM) fungi) and pathogens (both bacterial and fungal). The increased attention on these two groups is due to their direct influence, either positive or negative, on plant health or yield. In pot studies AM fungal root colonization tends to increase as soil reaches intermediate pH levels (5–6) but decline again as soils increase in alkalinity (Castillo et al., 2014; Johnson et al., 2005; Sano et al., 2002; Takács et al., 2006), and liming appears to promote AM fungal spore production (Wang et al., 1993). Changes in AM fungal community composition as detected in roots by molecular tools have also been shown e.g. (Gomes et al., 2015), although no studies to date have examined what the functional impacts (e.g. nutrient delivery, soil stability, antagonist defence) of these shifts. Changes in soil pH have led to a shift in *Rhizobia* species composition (Zhalnina et al., 2013b) (Durán et al., 2013), in particular colonisation of Rhizobium can be markedly reduced in highly acidic zones of the soil (Richardson et al., 1988). Thus, the improved conditions for rhizobia can have subsequent benefits for crop growth due to improved nodulation and increased N fixation (Jarvis, 1984), but again the functional impacts (e.g. nitrogen delivery) of these changes have yet to be fully explored. Indeed, liming an acidic soil is expected to improve nitrogen fixation through the increased growth of productive legume species, increased abundance of compatible rhizobia and reduced constraints inhibiting the infection and nodulation of the host plant. There is substantial evidence of liming impacts on micro-organisms such as bacteria and fungi and their role on biological processes (Table 1) and subsequent beneficial effects on for cropping systems.

Nematodes and worms respond strongly to liming. Earthworms, particularly anecic earthworms, appear to increase in abundance in response to liming (McCallum et al., 2016). It is expected that any increase in earthworms would lead to an increase in decomposition rates. The impact of liming on nematodes is complex, but there is evidence of increased nematode abundance (Van der Wal et al., 2009) and also changes in nematode community composition (De Rooij-van der Goes et al., 1995; Murray et al., 2006; Zhao et al., 2015). Microarthropods play a significant role in decomposition as well as predation of multiple groups of soil organisms. Comparatively few studies focus on microarthropods, however most of these show few effects of liming on microarthropods (Fountain et al., 2008; Van der Wal et al., 2009), although it has been suggested that increases in soil nutrients increase microarthropod densities (Cole et al., 2005). This could be due to the focus on just a few groups of microarthropods (e.g. *Collembola*) or a wide effect, but more research needs to be conducted in this area before any conclusions can be drawn.

The application of lime has been found to have significant impacts on soil biological processes (see Table 2). There is extensive literature on liming-induced increases in soil pH, which have significant cascading effects on soil N transformation processes. This in turn influences the supply of N to plants and the loss of N to the atmosphere or to groundwater.

Experimental evidence shows how liming can increase soil microbial biomass N as well as microbial activity (Kemmitt et al., 2006). Results from a long-term experiment at Rothamsted, UK show that there is a stabilization of microbial biomass N and microbial activity at pH values ranging between 5 and 7 (Pietri and Brookes, 2008). The mineralization of N in soils can also increase as a result of liming applications as demonstrated in two Northern Irish studies (Bailey, 1995; Stevens and Laughlin, 1996), which reported significant (but transient) increases in organic N mineralisation. It has been shown however that liming can either decrease N mineralization (Wachendorf, 2015) or not have any direct effect on N mineralization (Kemmitt et al., 2006). It is likely that repeated liming applications will increase soil N mineralization, but the overall impact of liming will depend on whether net mineralisation or net immobilisation ultimately occur based on the C:N ratio of plant detritus returned to soils (Bailey, 1995). Liming impacts are variable and strongly dependent upon the C:N ratio and the quality of the organic matter, especially the C:N ratio of particulate

Table 2
The impacts from liming on key soil biological processes (C and N) and functional effects on ecosystem services (ES).

Process	Major change	ES impacts	Reference
N microbial biomass	↑ Biomass	+ve (plant growth)	(Kemmitt et al., 2006; Pietri and Brookes, 2008)
N mineralisation	↑ NO_3 available	+ve (plant growth)	(Bailey, 1995; Kemmitt et al., 2006; Stevens and Laughlin, 1996)
N immobilisation	↓ Mineral N	−ve (plant growth)	(Wachendorf, 2015)
NO_3 leaching	↓ NO_3 loss potential	+ve (water quality)	(Gibbons et al., 2014)
NH_4 nitrification	↑ Microorganism activity	+ve (nutrient cycling)	(Bertrand et al., 2007; Kemmitt et al., 2006; Stiehl-Braun et al., 2011).
NO_3^- NO_2^- denitrification	↓ NO_3^- losses	+ve (water quality)	(Liu et al., 2010; McMillan et al., 2016)
Biological N fixation	↑ Plant available N	+ve (plant growth)	(Sommer and Ersbøll, 1996)
NH_3 volatilization	↑ NH_3 losses	+ve (air quality)	(Sommer and Ersbøll, 1996)
N_2O emission	↓ N_2O losses	+ve (air quality)	(Higgins et al., 2012; Kunhikrishnan et al., 2016)
C mineralisation	↑ OM mineralisation	−ve (carbon regulation)	(Paradelo et al., 2015)
C immobilization	↑ CO_2 losses	−ve (carbon regulation)	(Kemmitt et al., 2006)
C microbial respiration	↑ Long-term C gain (short-term C losses)	+ve (carbon regulation)	(Fornara et al., 2011)
C microbial biomass	↑ Microbial activity	+ve (carbon regulation)	(Biasi et al., 2008)
C supply from root exudates	↑ Long-term C gain	+ve (carbon regulation)	(Meharg and Killham, 1990)

↑ = increase; ↓ = decrease; +ve = positive; −ve = negative.

fractions (Wachendorf, 2015). Where liming increases mineralization there is a subsequent increase in available N in the form of ammonium-N which has implications for plant growth and N leaching risk.

Liming impact on NO_3^- concentrations in soils has major consequences for crop nutrient uptake and thus crop yield (see section on crop yield). In the absence of adequate plant uptake or due to excessive rainfall there is a risk of NO_3^- leaching. Nevertheless, a modelling study of different nutrient budget scenarios concluded that liming would reduce NO_3^- leaching (Gibbons et al., 2014). Several studies have shown the positive correlation between liming and soil N nitrification (Curtin et al., 1998; Kemmitt et al., 2006), which is strongly influenced by changes in microbial community composition and by O_2 supply (i.e. ± aerobic conditions) (Bertrand et al., 2007). Where O_2 supply is limiting anaerobic conditions will develop promoting denitrification processes. Denitrification is a reducing reaction where N is lost from the soil as a gas (N_2O, N_2). There is evidence that liming can reduce the production of gases associated with denitrification, although factors such as soil type, temperature and antecedent N source influence the extent of reduction (Liu et al., 2010; McMillan et al., 2016). Microbial community composition strongly affects denitrification activity, thus there are different soil pH responses, e.g. bacterial denitrification is impacted by liming, but fungal denitrification is not (Herold et al., 2012). The fixation of N is promoted in most circumstances by liming (Newbould and Rangeley, 1984). Nevertheless, the amount and rate of fixation activity will be strongly influenced by the composition of the microbial community (Zhalnina et al., 2013a). The level of N fixation has implications on the amount of N available for plant uptake.

Any consideration of liming impacts on N transformation must include gaseous processes. An extensive review of the impact of liming on greenhouse gas (GHG) emissions by (Kunhikrishnan et al., 2016) shows that while liming increased CO_2 flux and the oxidation rates of CH_4, N_2O emissions decreased. Quantification of this liming effect showed there was four times decreased N_2O emissions from a limed soil (pH 7.0) compared to a soil with pH 4.5 (Baggs et al., 2010). Another key gaseous process is volatilization and this is increased by liming which raises NH_3 emissions (Sommer and Ersbøll, 1996). In terms of the direct net liming impact on GHG flux there is evidence that liming is not a sound mitigation strategy (Gibbons et al., 2014; Higgins et al., 2013) and thus, overall GHG emissions are increased after liming.

The regular application of liming materials to soils greatly contributes to reductions in soil acidity while enhancing the availability of reactive forms of N (i.e. NO_3) for plant uptake. Although agricultural liming greatly support plant biomass production across many agro-ecosystems worldwide (Haynes and Naidu, 1998; Norton and Zhang, 1998), long-term liming effects on soil C stocks are not well understood. From a global change perspective, agricultural liming is considered a net source of atmospheric CO_2 mainly because liming applications are assumed to be associated with an emission factor of 100%, whereby all C in lime will be released into the atmosphere (IPCC, 2006). Recent evidence, however, from long-term permanent grassland studies show that regular liming applications can be associated with increases in soil C stocks (Fornara et al., 2011; Sochorová et al., 2016) or at least with no changes in C content and C pools between limed and non-limed grassland soils (Fornara et al., 2013). Fornara et al. (2011) determined that the contribution of inorganic C was very small and that the bulk of C accrual in limed soils was via organic C inputs. Therefore, the long-term effects of liming on grassland soils may benefit C accumulation (or at least do not lead to net C losses), although liming in combination with other practices (i.e. organic nutrient applications) are management alternatives that may deliver multiple ecosystem services including high plant productivity and soil C sequestration.

It is not clear, however what set of biogeochemical mechanisms interact to determine whether liming causes a net gain or a net loss of C. In the short-term liming applications will increase biological activity in soils either directly by providing labile C forms to microbial use (Biasi et al., 2008; Zelles et al., 1990) or indirectly by increasing soil pH and favouring microbial groups which are less C-use efficient (i.e. respire more C per unit of degradable C) thereby resulting in higher C losses via soil respiration (Fornara et al., 2011).

There are however, potential mechanisms through which liming can benefit soil C accumulation and which need further investigation. Liming, for example can increase the volume of labile root exudates entering the soil (Meharg and Killham, 1990), thus enhancing C inputs to soil ecosystems. Also geochemical mechanisms associated with the dissolution of lime in soils could increase carbonic acid (HCO_3^-) concentrations in soil water solutions, which in turn could sequester 25-50% of lime C as evidenced in moderately acid soils (Hamilton et al., 2007). Moreover, regular long-term liming applications may contribute to the redistribution of C from labile to more humified-recalcitrant soil organo-mineral C fractions (Fornara et al., 2011; Manna et al., 2007).

Long-term net liming effects on soil C stocks are likely to be dependent on the interaction between different environmental variables and other management practices. For example positive liming-induced effects on soil C stocks may be significantly reduced when lime is added together with key inorganic nutrient fertilizers such as N and P (Sochorová et al., 2016), although evidence of positive relationships between C with N, P and S indicate a degree of stability in C:N:P:S ratios and illustrate the complexity of how other factors (in conjunction with liming) influence soil C stocks (Kirkby et al., 2011). Also liming effects on soil C content may be mediated by changes in the soil microbial community whose responses to increases in soil pH could be very variable (Kennedy et al., 2005; Pawlett et al., 2009). Finally, liming may influence soil C content by affecting the activity of microbial groups which produce C-acquiring extra-cellular enzymes such as β-1,4-glucosidase (BG), which is required for the hydrolysis of cellulose (Cenini et al., 2015). A decrease in BG activity is thought to reduce the amount of C-rich detritus processed by microbes and then incorporated into more recalcitrant soil C pools.

3.3. Liming impacts on soil nutrient processes, minerals and heavy metals

Liming influences the availability of all mineral and toxic elements in soils by having impacts on pH which affects a range of processes including biological and biochemical activity, mineralization of organic bound elements, chemical adsorption, precipitation reactions and plant uptake of nutrients. But, it also has impacts by adding substantial quantities of both Ca and CO_3 which impact the biological availability and utilisation of both cationic (specifically Mg and K) and anionic (specifically P) forms of nutrients in soils, respectively. The addition of lime to soil triggers buffering processes which change the balance of exchangeable cations and the dissolution of Al, Mn and Fe minerals. Thus, there is a complexity to liming impacts which is reflected in a series of wide-ranging simultaneous effects and subsequent changes to soil processes. For the purposes of this review the focus will be on macro and micronutrient (trace elements) which are important for plants, with some consideration of heavy metals. Within this context selected key liming impacts (with related processes) is presented in Table 3 and further discussion is given below.

The impact of liming will be affected by the soil type and mineralogy of the soil which is being managed. In the tropics soils are characterised by having surfaces bearing variable charge, which are produced by reactions on the surface or edge of the minerals, and is greatly affected by pH (Mokwunye et al., 1986), whereas in temperate regions soils tend to be dominated by mineral types which are less effected by pH. Common variable charge minerals in tropical soils include iron (Fe) and aluminium (Al) oxides and hydroxides (hematite, goethite, lepidocrocite and gibbsite, boehmite, respectively). Phyllosilicate clay minerals such as kaolinite, halloysite and chlorite also show variable charge properties. The combination of surface area and magnitude of net positive charge on minerals renders them more or less efficient adsorbers of nutrients.

Nitrogen (N) is the macronutrient which is required in the largest amounts by plants and as such is often the most limiting nutrient. After N requirements, phosphorus (P) is often considered the most important nutrient for crops. (Haynes, 1982) reported that liming can increase soil P availability due to the mineralization of soil organic P and by the amelioration of Al toxicity, which enhances root growth in plants (Delhaize et al., 2004). Because extremely acidic soils ($pH < 4.2$) have toxic Al levels, it is sometimes difficult to determine whether a liming effect is due to the amelioration of Al toxicity or P deficiency. Liming can have a P-sparing effect which decreases the fixation of inorganic P by soil colloids (Kamprath and Foy, 1985) and stimulates the uptake of P by plant roots (Higgins et al., 2012). The strength of adsorption of phosphate onto soil surfaces is affected by pH and the effect is dependent on the predominant clay minerals and types of organic matter in soils. Generally, adsorption is weakest at neutral pH and increases with increasing acidity. Similarly, precipitation of phosphate with metal ions is common in soils and is effected by pH, due to the effect of pH on the availability of the metal ions. As pH declines into acidity, metal ions such as Fe, Al, Mn, Zn and Cu all become more available, these become more toxic to plant and microbial growth, but they also become more available to precipitate out anionic phosphate and organic phosphorus forms such as phosphate monoesters. Likewise, as pH increases into alkaline conditions metals such as Ca and Mg become more available and precipitate out phosphate and make it unavailable. These impacts on precipitation have practical impacts on the use of fertilisers such as rock phosphate which is essentially a P rich calcium carbonate whose dissolution is reduced at high pH primarily because soil is saturated with Ca while at acidic pH this form of phosphate dissolves readily (Hinsinger and Gilkes, 1997). The complexity of the impact of liming on phosphate availability and its biological utilisation is further complicated by the prevalence of different phosphate species at different pH. Plants and microbes have preferences for the utilisation of these different forms of P which may not match the soil pH. There is preferential uptake of $H_2PO_4^-$, which has its optima at pH 5 and whose availability declines rapidly in both directions away from this optima. The overall effect of these changes in pH is greater amounts of plant available P and greater plant uptake which is beneficial for crop production in the range of pH between 5.5 and 6.5 and this should be target of liming management for phosphorus (Barrow, 1987). At the same time these changes are coupled with increases in the potentially mobile P pool which means that liming may increase the risk of P loss from land to water (Murphy, 2007). The rate and nature of soil process changes varies between different soil types e.g. short term effects (i.e. after 9 months) where liming negatively affects P availability have been reported (Viade et al., 2011).

Table 3
The impact of liming on soil chemical processes of selected macronutrients, trace elements and heavy metals

Nutrient/element	Process effect	Reference
Phosphorus	Increased organic P mineralization	(Haynes, 1982)
	Increased risk of P loss	(Murphy, 2007)
	Changes to plant available P	(Condron et al., 1993; McDowell et al., 2002)
Potassium	Increased K adsorption	(Bolan et al., 2003)
	Increased risk of K deficiency	(Bailey and Laidlaw, 1999)
Sulfur	Increased SO_4^{2-} mineralization	(Bolan et al., 2003)
	Increased SO_4^{2-} immobilization	(Valeur et al., 2002)
	Greater release of SO_4^{2-} and more risk of S loss	
Calcium	Increased Ca in the soil solution	(Bailey, 1995)
Trace elements	Increased adsorption of B, Cu, Co and Zn	(Bolan et al., 2003)
	Increased Se availability	(Öborn et al., 1995)
Heavy metals	Increased Cd immobilization	(Hong et al., 2014)
	Increased plant uptake of Mn, Cd, Pb, Ni	(Blake and Goulding, 2002)
	Increased risk of heavy metal leaching	(Fageria and Baligar, 2008)

Evidence from several studies indicates that liming can increase potassium (K) adsorption (Bolan et al., 2003). Results from a white clover study found a significant interaction between lime and K with reduced plant growth (petiole length) at the highest lime treatment due to K deficiency (Bailey and Laidlaw, 1999), much of the impacts on the availability of K are associated with the impact of pH on the release of K from interlayer spaces in clays. For sulphur (S) the increase in soil pH caused by liming can increase the mineralization of SO_4^{2-} from organic matter and also release SO_4^{2-} from Fe and Al sulfates (Bolan et al., 2003). Elsewhere long-term studies show that liming increases S immobilization (Valeur et al., 2002). Probably the greatest and most direct liming effects are the increased levels of Ca in soil (or Mg when dolomite lime is applied). Subsequently, the large additions of cations (Ca, Mg) directly influence the composition of the soil solution.

The response of trace elements to soil pH via liming is variable and plant availability is specific within a pH range. Because soil processes (such as chelation and precipitation) are pH dependent the strength of influence from liming is different for each trace element. This has implications for plant availability and crop uptake ability. Thus, at $pH > 7.0$, the availability of Zn is reduced, while liming increases the adsorption of Cu and B (Bolan et al., 2003). In contrast, the availability of Se has been shown to be increased by liming (Öborn et al., 1995), while there do not seem to be clear positive or negative effects on Mo (Bailey and Laidlaw, 1999). As regards heavy metals (e.g. Al, Mn, Cd, Mn, Hg, Pb, Ni), the behaviour of these elements also varies. For instance, increased soil pH causes the adsorption of several heavy metals (Al, Mn, Pb, Ni, Cr) (Bolan et al., 2003), while Hong et al. (2014) observed greater Cd immobilization as a result of liming. Consequently, in limed soil there is reduced solubility potential and thus less risk of heavy metals being lost through leaching (Fageria and Baligar, 2008). These soil process changes have implications for plants. (Blake and Goulding, 2002) measured the metal accumulation by oak trees at soil pH 4 and 7 and found there was between 3 to 10 times greater concentrations of Mn, Ni and Cd in leaves at the lower pH. Likewise crop (carrot, spinach, wheat) metal uptake (Cd, Ni and Zn) was found to be less in limed soils (Hooda and Alloway, 1996) and with obvious implications for food safety and animal and human health. Overall, the impacts of liming on heavy metals are considered positive, because their toxicity is reduced.

3.4. Liming impacts on soil physical condition

The impacts of liming on soil physical condition are via pH change which drive many soil chemical processes (as described above). The composition of the material added can affect the cation composition (valence and ionic radius) and the ionic strength of the soil solution. The rate at which liming changes soil structure depends on the solubility of the added material (including particle size) and the buffering capacity of the soil. The mechanisms by which cations and overall electrolyte concentration alter soil structure and hence soil functions are well established. For example, increasing the ionic strength of the soil solution will favour coagulation and the formation of micro-aggregates that in-turn will drive increased hydraulic conductivity and drainage (Quirk and Schofield, 1955). Liming changes the composition of cations in the soil solution which for sodic soils can result in soil structural improvement. Valzano et al. (2001) reported on the ameliorative effect of liming on soil physical properties as evidenced with less dispersion, decreased penetrometer resistance, higher infiltration, and greater water availability. Another liming benefit observed by Valzano et al. (2001) was that the total soluble cation concentration was maintained while in comparison there were reductions in soluble cations after gypsum was applied. A liming study on sodic soil found effects on soil physical properties were still evident after 12 years even though the presence of lime could no longer be detected (Bennett et al., 2014). In addition, Bennett et al. (2014) reported that liming at 5 t/ha significantly improved the aggregate stability and increased hydraulic conductivity of soil. These findings are important, because improved hydraulic conductivity is an indication that soil function is improved.

Under field conditions responses of soil physical conditions to liming are often not clear. This is due to the diversity of minerals (clays, oxides etc.), the nature of organic materials (quantity, origin and extent of decomposition etc.), the extent of binding and interaction between the minerals and organic matter and the form, solubility and timing of the lime application. Calcium is involved in forming complexes at the micro-aggregate scale (Baldock et al., 1994; Grant et al., 1992) and these may be stabilised to macro-aggregates by microbial activity (Chan and Heenan, 1999). In some instances, liming-induced soil structural changes are associated with an increase in earthworm and enchytraeid populations (Grieve et al., 2005). These changes in biota have been associated with increased total porosity and macroporosity, even though there was no effect of liming on aggregate stability. In contrast, another report stated that liming had no impact on soil structure that could be differentiated against the background earthworm activity (Davidson et al., 2004). These conflicting studies suggest that uncertainty of the significance of the interaction between liming, earthworms and soil structure. Moreover there are numerous studies where no significant soil physical improvement from liming is reported.

Time is a major factor in the formation of aggregates as a result of associations between calcium and organic matter. Aye et al. (2016) investigated water stable aggregation in two liming experiments but found that while macro-aggregate stability was increased in a 5-year-old trial the opposite was the case in a 34-year-old trial. This is counter to other observations that time improves the aggregate stabilising effect of lime (Baldock et al., 1994; Chan and Heenan, 1998). Much of the work linking calcium from lime or other ameliorants and soil aggregation has been undertaken on Alfisols (notably in Australia) and Oxisols (notably in Brazil). The extent to which these same mechanisms operate in other soils, particularly less weathered UK soils, needs to be clarified if lime application benefits soil aggregate formation and stability.

4. The impacts of liming on crops and grassland

4.1. Yield response of arable crops

Crop yields are determined by the interception of photosynthetically active radiation (PAR), the efficiency by which intercepted PAR is used for carbon fixation, and the partitioning of the organic carbon to the appropriate harvested tissue. Maximal growth and photosynthetic activity are predicated on the acquisition of adequate amounts of fourteen essential mineral elements, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), chlorine (Cl), boron (B), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), nickel (Ni) and molybdenum (Mo), and water (Grusak et al., 2016). Crops generally obtain these through their roots systems. Thus, any environmental factor that affects the acquisition of water or mineral nutrients by the root system will affect crop yields.

Liming soils affects the acquisition of both water and mineral nutrients through chemical, physical and biological effects on the soil. The pH of the soil solution influences the availability of the chemical forms of mineral nutrients that plant roots can take up (Section 3.3). The availabilities of all mineral nutrients, with the exception of Mn, are reduced in acid soils ($pH < 4.5$) and liming, by raising the pH of the soil solution, will increase their availability to plants (Taiz and Zeiger, 2010; White and Greenwood, 2013). In addition, liming can also reduce concentrations of Al^{3+} and Mn^{2+} that can be problematic in acid soils, which has the additional effect of increasing the retention and availability of K^+ (Section 3.3) (White and Greenwood, 2013). Liming, especially with dolomitic lime ($CaMg(CO_3)_2$) can also alleviate Ca and Mg deficiencies in crops.

Since plant roots must forage through the soil to acquire mineral nutrients, especially those that are relatively immobile in the soil solution such as P (White et al., 2013b), the physical properties of the soil are decisive for maximal crop production. Root growth generally requires a soil with a low bulk density that allows root penetration and has pores that are accessible to roots and allow drainage and air infiltration (Hamblin, 1985). Since liming soils can affect soil bulk density, soil strength, and the architecture of pore systems (Section 3.4), it can influence crop yields indirectly by affecting root foraging, although the magnitude of this effect is not known. Finally, since liming affects biological activities in the soil (Section 3.2), it can influence both the structure and chemistry of the soil and, thereby, influence crop growth and yields indirectly by influencing root system development and resource availability.

Although the liming of acidic soils improves the yields of most crops, the relationship between yield and soil pH differs between crops and is influenced by soil type (Fageria, 2009; Fageria et al., 2011; Farhoodi and Coventry, 2008; Goulding, 2016; Liu et al., 2004). For example, in the UK, potato crops generally achieve maximal yields at a lower soil pH than other crops such as wheat, beans or canola, although, the magnitude of this difference depends on field site (Fig. 4). Field beans (*Vicia faba* L.) appear most susceptible to soil acidity requiring a $pH > 6.0$, wheat (*Triticum aestivum* L.) requires a $pH > 5.5$, and swede (*Brassica napus* L.), kale (*Brassica oleracea* L.) and turnip (*Brassica rapa* L.) require $pH > 5.4$, whereas potato (*Solanum tuberosum* L.), for which low soil pH affords protection against common scab (AHDB, 2013), can achieve maximal yields at pH 5.0 (Goulding, 2016).

Since acid soils reduce crop yields worldwide, there has been much research to determine the relative tolerances of different crops to acid soils and the mechanisms enabling this tolerance (Fageria et al., 2011; Kochian et al., 2015). Exploiting the tolerance of crops to acid soils provides a complementary strategy to liming for bringing these soils into agricultural production (Kochian et al., 2015; White and Greenwood, 2013). There is considerable variation in the range of soil pH tolerated,

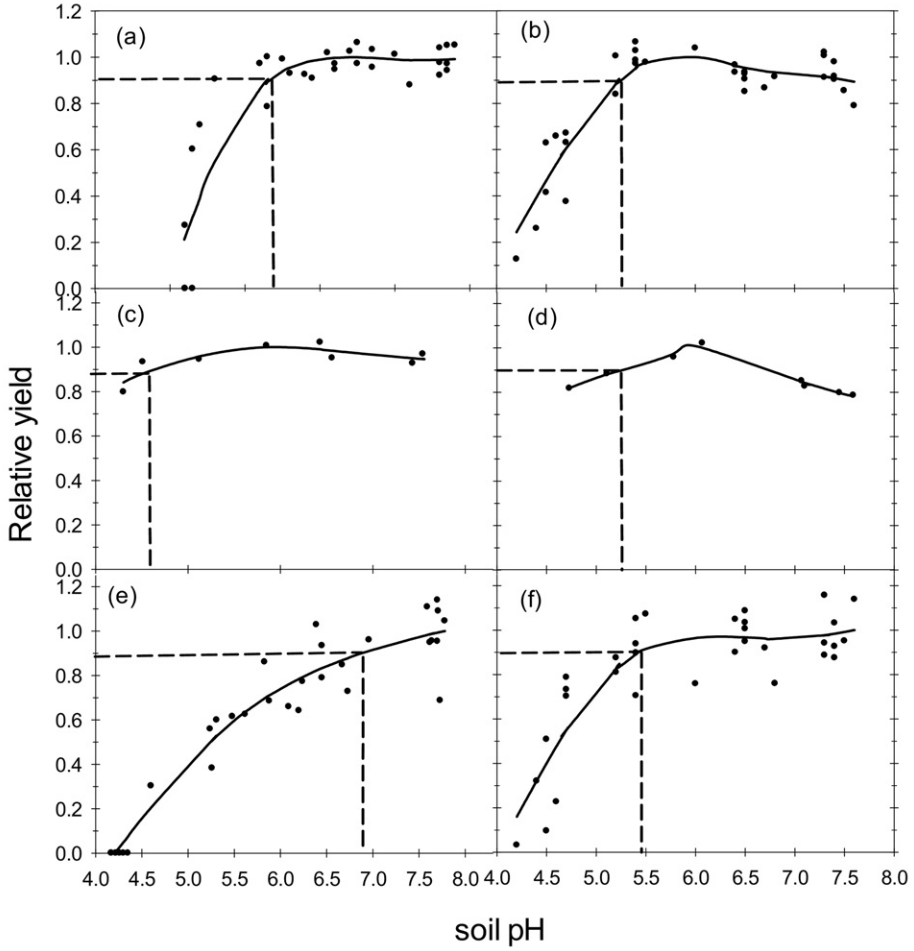

Fig. 4. Crop yield-soil pH relationship from the Rothamsted long-term liming experiment at two sites; Rothamsted (a) wheat 1996, (c) potatoes 1983, (e) beans 1990; Woburn (b) wheat 1996, (d) potatoes 1983, (f) oilseed rape 1991. The dashed lines indicate 90% relative yield.
Source: Data from the electronic Rothamsted Archive (eRA, 2017).

and the loss of yield to changes in soil pH outside this range, both between and within crop species (Fageria, 2009; George et al., 2012). In general, tolerance of acid soils is often related to an ability to prevent Al^{3+} toxicity and the consequent reduction of root growth (George et al., 2012; Kochian et al., 2015; White and Greenwood, 2013). This ability is often conferred by the release of organic acids, such as malate, citrate and oxalate, at the root apex (George et al., 2012; Kochian et al., 2015). These form Al-complexes and reduce the phytoavailability of toxic Al species in the root elongation zone. However, crop growth on acid soils can also be restricted by Mn^{2+} toxicity or by deficiencies of Ca, Mg, P or Mo (Fageria et al., 2011; George et al., 2012). In soils with low Al content, the beneficial effects of liming are often related to improved nutrient availability. In addition to the effects of liming on crop yield, it can also influence crop quality. For example it can improve nutritional quality by increasing concentrations of mineral elements required by livestock and humans (Soltani et al., 2016; White et al., 2012) and reduce physiological disorders and post-harvest losses resulting from insufficient tissue Ca concentration (Jemrić et al., 2017; White, 2017).

4.2. Crop rotation of arable crops

The 2015 British Survey of Fertiliser Practice shows there are distinct differences between which crops are limed (Table 4) (DEFRA, 2016). Table 4 shows that a quarter of sugar beet and brassica vegetable crops are receiving a lime dressing, while only 6% of winter wheat and field bean crops and 12% of spring barley and oilseed rape crops. Findings from a long-term experiment near Aberdeen, UK, concluded that a soil pH of 5.5 was the optimal level for all crops across the whole rotation (Walker et al., 2011). Special consideration should be taken for selected crops and The Fertiliser Manual (RB209) indicates where sugar beet is grown maintaining a pH of between 6.5 and 7.0 may be justified (DEFRA, 2010). Crop rotation is important because of the crop disease implications which are strongly influenced by liming and it can be modified to reduce the risk of disease (further discussion is below).

4.3. Disease implications for arable crops

Liming has important implications for the development of crop diseases, especially those which are soil-borne. As a generalisation, acidic soils tend to be more conducive to disease caused by fungi. Some disease effects from liming are due to indirect effects on nutrient availability for plant metabolic processes, particularly those affecting defence mechanism pathways. For example, increased potassium nutrition tends to ameliorate fungal diseases and pests, whereas less benefit is

Table 4
The crop area[a] receiving a lime dressing (%) for different crops in Great Britain

	Winter wheat	Spring barley	Sugar beet	Oilseed rape	Field beans	Brassica vegetables
Mean	6.2	12.8	24.4	11.4	6.1	26.5

[a] Based upon the mean of survey data between 1994 and 2015; source: (DEFRA, 2016)

seen for bacterial and viral infections (Perrenoud, 1990; Prabhu et al., 2007). Furthermore, liming impacts have consequences on plant susceptibility to pathogens and this is observed in contrasting ways (Marschner, 2011). Calcium is implicated in different signalling pathways, such as for Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR) (Gilroy et al., 2016). Other pathogens respond at specific pH values such as *Pythium ultimum* and *Fusarium oxysporum* produce more disease at pH values greater than 6 and 7 respectively, whereas their tomato host plant grew better at pH 5 though the mechanisms affecting these relationships are unknown (Alhussaen, 2012). A wide range of other crop diseases (fungal, bacterial, viral and oomycete) are influenced by both increases (liming) and decreases (not liming) in soil pH (Rengel, 1999).

Soil pH will not only affect resistance expression as indicated above, but also the survival and growth of the pathogenic organism itself. Common scab of potato is substantially reduced when soil pH is <5.2 (Koike et al., 2003). In the case of *Streptomyces* scabies (the causal agent of potato common scab) soil acidification provides effective control (Lambert and Manzer, 1991), however different *Streptomyces* spp. vary in their tolerance to soil pH. Therefore, the standard UK agronomic recommendations (RB209) advise farmers not to lime before growing potatoes (DEFRA, 2010). Previous studies have shown that liming increases the severity and likelihood of potato scab (Lacey and Wilson, 2001; Lambert and Manzer, 1991). The control of cavity spot in carrot (caused by *Pythium*), is pH sensitive. Increased control up to neutral pH corresponds with disease reduction and bacterial population increase, particularly fluorescent pseudomonads (El-Tarabily et al., 1996). Particular amongst the microbial community are Plant Growth Promoting Rhizobacteria (PGPRs), particularly *Pseudomonas* species that induce systemic effects in plants, both plant vigour and disease resistance. *Pseudomonas* growth and function are strongly affected by pH, usually detrimentally at low pH (Chin-A-Woeng et al., 1998; Crawford et al., 1993; Leinhos, 1994; Naseby and Lynch, 1999) and therefore liming can potentially have beneficial effects on induced resistance.

The severity of clubroot (*Plasmodiophora brassicae*) is known to be related to soil pH and soil Ca content (Myers and Campbell, 1985). Below a soil pH of 5.7 clubroot can be very problematic but it can be dramatically reduced by raising soil pH to 6.2, and virtually eliminated by increasing soil pH to 7.3. A recent survey of oilseed rape fields in the UK evaluated the efficacy of soil amendments such as lime to control clubroot (McGrann et al., 2016). McGrann et al. (2016) reported that liming can assist in the control of clubroot, but the results were not consistent across sites and years. At some sites the control ranged from nil (0%) to 95% at others, while the incorporation of lime by ploughing was considered to be important. Another study in Scotland found that liming was ineffective in controlling clubroot (Knox et al., 2015). This suggests that the complex interaction of nutrients, pH and inoculum load on clubroot development and expression which can be greater than the changes induced by liming. In addition, crop disease development varies between cultivars and thus the level of susceptibility differs.

4.4. Grassland liming impacts

4.4.1. Biomass production response from liming on grassland

Liming of grassland is a common management practice. There is substantial evidence of a positive biomass response which is beneficial for both grazing and conserved herbage production (e.g. silage). In some instances grassland biomass responses to lime are only evident for a short period (i.e. 3–5 years) (Stevens and Laughlin, 1996). Such short-term production benefit from liming could be because reserves of readily mineralizable soil organic N are mined and depleted over this time. In contrast, a long-term study of pasture management treatments in Scotland showed that after 7 years following lime application there were no indications of declining grassland productivity on limed treatments (Common et al., 1991a). Likewise, an increase in long-term production of 1.0 t/ha from liming (compared with a control) was observed in an 18 year-long study in mid-Wales (Davies, 1987a). Biomass responses from liming are quite variable and depend upon the local acidifying pressure, the antecedent soil pH and the influence of other management practices. Consequently, a significant number of studies have report no change in biomass production and in other cases a significant decrease in biomass has been reported (Cregan et al., 1989).

The longevity of positive liming responses may be affected by the underlying soil chemical status. For instance, there is a significant interaction between Ca and P in perennial ryegrass with lime inducing a P-sparing effect (Bailey, 1991). Therefore, for intensively managed grassland the effectiveness and biomass response of lime appears to be strongly related to the effect of lime on nutrient availability (as described above in Section 2.3). It is likely that a major component of liming responses on pastures is due to the stimulatory effect of increased soil pH on the microbial mineralization of soil organic N (Bailey, 1995). The degree to which soil processes influence biomass production will vary according to soil type, but also according to sward species composition.

The initial extent (and therefore length) of biomass responses to liming is strongly related to the grassland species present in swards. An evaluation of several Northern Irish grassland field experiments showed that positive liming responses were directly proportional to the initial content of perennial ryegrass in the sward (Bailey, 1997). Bailey (1997) stated this was because the perennial ryegrass was better than other grass species at competing for mineral N following lime application. There are also other factors which explain differences in species productivity following liming. Hayes et al. (2016) showed that liming increased lucerne, phalaris and cocksfoot herbage biomass by 150, 30 and 20%, respectively, but has no effect on chicory or tall fescue biomass. The difference in responsiveness of grassland species to liming is likely to be associated with the wide range in acid sensitivity across species. Thus, the beneficial effect of liming on production by some grassland species has been described as providing a ‘protective effect’ against Al toxicity (Poozesh et al., 2010). Jarvis (1984) found significant effects of nodulation on white clover cultivars and greatly reduced the number of nodules that formed. The effect of lime on nodule development was interesting because it significantly increased clover biomass yield (via increased N supply) and there were different responses between clover cultivars. Indeed, the increased survival of desirable species such as white clover as a result of liming may be beneficial for grassland productivity (Bailey and Laidlaw, 1999). Grassland productivity is strongly influenced by sward composition and liming is just one management practice which will both increase production and alter sward composition. The relationship between liming and sward composition (species richness) has received much attention in ecological studies (Kirkham et al., 2014; Storkey et al., 2015) (see further discussion below in Section 5 The impacts liming on biodiversity). In contrast, there has been little reported on the below-ground grassland impacts of liming, however recent evidence from a long-term grassland experiment shows how liming significantly contributed to decrease total root mass and increase root mass decomposability (Heyburn et al., 2017).

4.4.2. Liming effects on mineral content and herbage quality in grassland

The full impact of liming grassland for agricultural production requires consideration of the effects on mineral content and herbage quality. Indeed, because the application of lime changes the sward botanical composition there are subsequent effects on mineral content and herbage quality. These changes have important implications on animal performance for grassland based production systems. A long-term (18 years) grazing study in mid Wales showed that liming significantly increased the herbage content of both Ca and Mg (due to higher plant uptake) (Davies, 1987b). The effect of herbage mineral content strongly depends upon the type of limestone used. Thus, the use of dolomitic lime ($CaMg(CO_3)_2$) can also improve the Mg content of swards and help to prevent Mg deficiency in grazing livestock (Riggs et al., 1995). In comparison, chalk/ground limestone ($CaCO_3$) increases Ca uptake

(Fystro and Bakken, 2005). Hamilton et al. (2012) reported that liming improved herbage mineral composition (increased Ca and/or Mg and decreased K) such that the risk of grass tetany was reduced for cattle grazing tall fescue. At different times during the season (i.e. hay cuts) Poozesh et al. (2010) reported that liming can increase the N and P contents of herbage, but not the K content. In addition, Sanders et al. (1986) showed that liming reduced the uptake of Zn, Ni and Cu by ryegrass. These results indicate that liming can reduce the risk of heavy metal toxicity and lower the likelihood of uptake by grazing animals.

Liming can significantly impact herbage quality characteristics. A long-term sheep grazing experiment in Scotland, UK showed that at times on liming significantly increased organic matter intake and digestibility (Common et al., 1991b). Common et al. (1991b) however did not detect significant liming effects across the different sites and seasons. Nevertheless, the overall impact of liming on herbage quality had a positive and significant effect on animal performance in terms of liveweight gain and the number of sheep grazing days. In an upland study in Wales, Yu et al. (2011) found that lime significantly increased the levels of several herbage quality variables (ash, water soluble carbohydrates, crude protein, neutral-detergent fibre, modified acid-detergent fibre, metabolizable energy). Yu et al. (2011) commented that the positive effects on herbage quality on limed grassland corresponded with a greater livestock carrying capacity and higher liveweight gain compared with an unlimed control. Liming therefore had a significant influence on livestock performance. At least part of this specific liming impact on grassland was probably due to the shift in sward species composition (addition discussion is given in the biodiversity section). Due to the influence of several other biophysical factors (such as soil and climate) there are situations where liming does not significantly improve mineral content or herbage quality, however there is previous evidence that liming can change herbage mineral content and quality characteristics and these are important additional indicators of liming impacts for grassland-based livestock production systems.

5. The impacts of liming on biodiversity

The impacts of liming on biodiversity will be very context specific, depending on the species pool present at a site and the ability of species to disperse and establish at a site. Soil pH is a major driver of plant community composition (Ellenberg, 1988) and altering soil pH by liming will shift composition, but because of variable numbers of species with different pH optima in the species pool, there may be both positive and negative impacts on diversity. Species richness generally peaks in neutral soils, and declines rapidly as pH drops below 5 (Merunková and Chytrý, 2012; Olsson et al., 2009). In the Park Grass Experiment, lime addition had no impact on diversity where plots were unfertilised or had sodium nitrate added. However, where the nitrogen fertiliser was ammonium sulphate, lime addition significantly increased species richness (Crawley et al., 2005). Limed plots also saw enhanced recovery of species richness from the long-term impacts of nitrogen deposition (Storkey et al., 2015). Liming alone boosted species diversity in a ten year experiment in the Pyrenees, in addition it increased productivity (Poozesh et al., 2010). Moreover lime has also been used in restoration studies to counteract long-term acidification (de Graaf et al., 1998). The reduction of liming in the uplands combined with continued acidification has led to the loss of species of base rich habitats (McClean et al., 2011) and an increase in acid tolerant species (Stevens et al., 2010). This is in line with general patterns across grassland systems in the UK, with increased intensification of more productive grasslands, but evidence of reduce exploitation in more marginal grasslands (Carey et al., 2008; Pakeman et al., submitted).

Soil mesofauna responded to lime additions in different ways in the soil biodiversity experiment at Sourhope; mites increased in overall abundance, collembolans were unaffected and enchytraeid worms decreased (Cole et al., 2006). There were also significant shifts in soil mesofauna composition. Soil macrofuana such as earthworms can also be affected by soil pH; as soils are limed there can be both shifts in composition of groups such as earthworms and increases in population numbers (Cole et al., 2006; McCallum et al., 2016). However, as earthworms are an important food resource for birds such as lapwing *Vanellus vanellus*, liming could be an important management tool for providing food resources to declining wading birds (McCallum et al., 2015) and potential slow or reverse their long-term population decline (Hayhow et al., 2015). Reproductive success in birds can also be limited by the availability of dietary calcium from invertebrates, with good evidence available for reproductive limitation in acid areas (Graveland and Drent, 1997) and its alleviation by supplementation (Mänd et al., 2000).

The impacts of liming on higher trophic levels may be as a result of changes in soil pH and calcium availability. However, most impacts will be mediated via changes in the plant community, with impacts through changes in litter quality and other inputs into the soil, changes in food quality for herbivores of all sizes and their cascading effects on food availability and food quality for higher trophic levels. Many liming impacts will be neutral in biodiversity terms, such as the change in dominance from one common plant species to another, but there may be positive impacts on some groups. There is now some evidence that some birds species can potentially benefit, but the impacts of liming on biodiversity separate from other aspects of agricultural intensification is still lacking in evidence for many groups of organisms.

6. A qualitative framework of the liming impacts on the processes and functions of soils and crops

Liming has extensive and distinctive positive and negative impacts on the soils, arable land (crops), grassland and the biodiversity across the landscape. The approach outlined by the UK National Ecosystem Assessment (UK NEA, 2011) is used here to discuss the significant impacts in terms of provisioning, regulating, supporting and cultural services. To illustrate this, the extensive and temporal nature of liming impacts is presented in a simplified qualitative framework (Fig. 5). Lime is placed at the centre and the effects of liming are shown as a ripple-like pattern. This captures the importance of time to lime-induced process change, and each 'ripple' (oval-like line) shown represents an increasing time period. The impacts from liming are positioned in an approximate temporal sequence (albeit in two halves), but the figure does not consider or account for the spatial scale effects of liming. In addition, this conceptual framework (Fig. 5) provides an indication of the potential influence of management practices on the rate at which lime causes process changes. Thus, the time difference is illustrated with dashed oval-like lines representing management which increases the reaction time of lime (e.g. ploughing and incorporating lime in comparison with not ploughing i.e. direct drilling (Conyers et al., 2003)); in comparison solid oval-like lines represent management practices which are slower (e.g. top-dressing lime or no ploughing).

The left half side of the '*lime ripple*' (Fig. 5a) is focused on processes and is described in soil properties or crop trait type terms. Thus, the innermost 'ripple' of Fig. 5a has soil pH and several cations that are most directly impacted as a result of liming. These soil properties are changed almost immediately upon liming and the time scale of change is over a period of weeks. Next a number of soil properties are listed and these involve soil biological, chemical and physical processes relating to: phosphorus (P), potassium (K), sulphur (S), N transformations, heavy metals (HM), soil biota, soil organic carbon (SOC), nitrous oxide (N_2O), carbon dioxide (CO_2) and structure. These soil properties vary in their rate of change due to liming, but the time scale for some changes varies from months to years. The outer two 'ripples' correspond to some indirect liming impacts that have been reported for crops (in terms of growth and disease for arable crops and species composition for grassland) and biodiversity. These are the slowest and perhaps most complex impacts that can take years to decades to be detected. The right half of the '*lime ripple*' (Fig. 5b) is described using ecosystem service (ES) terminology (UK NEA, 2011) that relates to the function performed or

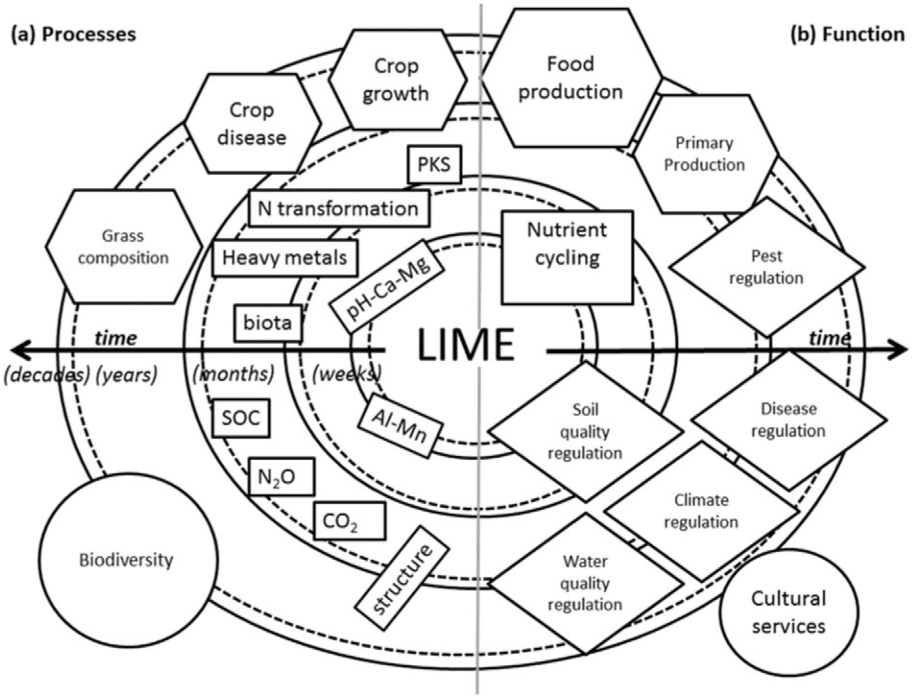

Fig. 5. A qualitative framework of liming impacts for soils, crops and biodiversity with a chronological scale for (a) properties and processes, and (b) function (ecosystem services) within an agricultural ecosystem. The solid circular/oval lines represent the time span for the standard management practices; the dashed circular/oval lines represent shorter time for improved management practices. Components in rectangular boxes represent different soil properties, soil processes and related ecosystem services, components in hexagonal boxes represent crop or grass responses and related ecosystem services, components in diamond boxes represent regulation type ecosystem services and components in circles represent biodiversity and cultural services.

the output from the soil or plant. Thus, the inner 'ripple' of Fig. 5b which has the most rapid changes corresponds with nutrient cycling and soil quality regulation. The next 'ripple' at the month to year time scale are services related to plant and soil: provisioning (food production), climate regulation, water quality, pest and disease regulation, and other supporting services (water cycling, primary production). The outer 'ripple' includes the cultural services that can take from years to decades to change. This qualitative framework provides the reader with information on the complexity and timescale of expected impacts of liming soil and as such provides information on what impacts managers can expect to have in what period of time by adding lime to their system.

Table 5 provides specific examples of the association between ecosystem processes (Fig. 5a) with corresponding ecosystem services (and a useful indicator) (Fig. 5b) and a brief description of the subsequent liming impact. Probably the most rapid liming impact response (the inner 'ripple' of Fig. 5b) on ES is found with nutrient cycling (a supporting service). Soil biota plays an important role in several biological processes such as decomposition, mineralisation, nitrification and mobilization. The application of lime to a field soil acts like a 'shock' to the soil-plant system whereby the pH increases and numerous processes are altered. From Table 1 it is clear that in most cases the impact of liming results in increased activity of soil biota. Consequently, the rate of nutrient cycling processes are increased and soil function is impacted the delivery of ES. Nutrient cycling is also influenced by other factors including weather and land use; thus it is difficult to distinguish the impacts of liming at a large scale. Nevertheless liming impacts are distinctive and the subsequent changes have important consequences for nutrient storage and flux. At short time scales there can be rapid liming changes in soil processes (e.g. neutralizing soil acidity) that deliver services on soil quality regulation. Soil pH is a simple and effective indicator of soil quality regulation (Table 5); which influences services such as nutrients filtering and the dynamics of the soil microbial community (Smith et al., 2013). In contrast, other processes which influence soil quality regulation (e.g. soil structure changes) are slower to be impacted by liming.

Several regulating services are impacted by liming, but respond more slowly than nutrient cycling. Changes (increases or decreases) in C storage can impact climate regulation. Thus, long-term permanent grassland studies show that regular liming applications can increase soil C stocks (Fornara et al., 2011) (Table 5) potentially reducing net GHG release to the atmosphere. The soil pH shift caused by liming can reduce N_2O emissions (Higgins et al., 2012) which improves air quality and climate regulation (both beneficial ES outcomes). Water quality regulation is strongly connected to nutrient cycling and the application

Table 5
Selected examples showing the association between ecosystem processes, ecosystem services (with an indicator) and the subsequent liming impact on ecosystem services.

Ecosystem process	Ecosystem services	Indicator	Liming impact on ecosystem services	Reference
Mineralization	Nutrient cycling	NH_4^+	Increase in amount of organic N mineralised	(Bailey, 1995)
Neutralizing	Soil quality regulation	Soil pH	Increasing soil pH	(Conyers, 2002)
Carbon microbial respiration	Climate regulation	Soil organic carbon	Increase in carbon storage	(Fornara et al., 2011)
Nitrification	Water quality regulation	NO_3^-	Increase risk of nitrate leaching	(Ridley et al., 2001)
Pathogen development	Disease regulation	% crop disease infestation	Reduction in clubroot severity	(McGrann et al., 2016)
Photosynthesis	Primary production	Above-ground plant biomass	Increase in plant biomass	(Stevens and Laughlin, 1996)
Crop growth	Food production	Crop yield	Increase in crop yield	(Goulding, 2016)
Biodiversity development	Cultural	Biodiversity richness	Increase in wading birds	(McCallum et al., 2016)

of lime has been shown to effect the amount of nitrate leaching from grassland (Ridley et al., 2001) (Table 5). But the impacts on water quality are indirect which explains why the response is often slow.

Above-ground liming impacts are observed via different crop and plant responses. Clear ES effects have been observed on disease regulation e.g. liming reduces the severity of clubroot (Table 5). The positive impact of liming on plant growth increases primary production (Table 5). Food production is often considered to be the most important provisioning service. Overall, for most arable crops liming increases crop yield and hence on food production. This positive ES outcome is indirect and is via the impact that lime has on nutrient cycling (soil fertility) (Goulding, 2016) (Table 5). The liming of grasslands can have beneficial impacts on biomass production, mineral content and herbage quality and these effects are all positive for livestock performance and thus for food production. Biodiversity responses to liming are likely to take several years to fully develop. It is not unknown for relatively rapid changes in sward composition or in earthworm abundance, but higher trophic effects (e.g. a cascading effect on birds) are generally much slower. Where there are significant areas of lime applied there is the potential for landscape scale impacts. Liming can shift the composition and abundance of flora and fauna species; e.g. recent evidence of increases in wading birds (McCallum et al., 2016) (Table 5). Liming impacts on biodiversity can potentially modify landscape ascetics which are a cultural ES.

7. Recommendations and implications

7.1. Recommendations for future research

This review has evaluated many potential liming impacts on a wide range of soil processes, crops and biodiversity. There remain several areas where future research is required. A better mechanistic understanding is needed in at least broad two areas: (*i*) at process level (i.e. biogeochemical processes) and/or for a specific organism (insect, bird or plant) focus, and (*ii*) at ecosystem level.

7.1.1. Process and organism level research

Recent progress in better understanding liming impacts on soil biota is encouraging. Much more information is needed on the impacts on soil biology in general, but specifically on mycorrhizal fungi, archaea and micro-arthropod species in a greater variety of environmental conditions, especially a wide soil pH gradient. New developments in molecular tools enable the improved detection and understanding of these groups. There is a lack of data on soil structural effects from liming (and from different forms of lime, i.e. calcareous versus magnesian limes). In particular, the length of time for liming effects to be detected requires further investigation. Related to this is detailed knowledge on how all liming materials influence the aggregation of soil particles. Previous research on liming has highlighted the role of precipitation processes and the development of ionic bridging, but the extent of soil types where this develops is not clear. Recent concerns about soil fertility and the sustainability of current nutrient management practices could be overcome if the far-reaching effects of liming were investigated in a more thorough manner. Thus, in terms of liming effects on soil chemistry, there remains a lack of knowledge of the interaction effects such as with P, K and S. Moreover, not all soil nutrient tests adequately account for the effect of soil pH (Edwards et al., 2016). There is also a significant lack of studies on the liming impact on soil physical properties and soil structural condition. Future studies need to cover a wider range of soil types and account for recent changes in crop rotations.

The liming impact on arable crops has mostly focused upon the most common crop types. Therefore, with the importance of the need for increased diversification in crop rotations there is a requirement that new field experiments are established to determine the liming response for minor arable crops and vegetables. For example, in the UK there is little understanding of the yield response to liming for several crops, notably triticale, rye, oats, linseed, lupins and brassica vegetable crops. Much previous work has focused solely on grain yield responses, but little is reported on crop quality e.g. grain mineral content. For grassland systems there is a need for a better understanding of the longevity of the biomass responses in order to better define when lime needs to be re-applied. Future research is required to evaluate the biomass response to liming for grasslands with different sward compositions and also on estimating potential changes in mineral content or herbage quality of limed grassland. Such information is valuable because of the need to fully understand the impacts of liming on livestock performance. Biodiversity impacts from liming are of continued interest. For instance, in the UK there remains interest in determining whether liming is beneficial for upland bird populations and also what other botanical or faunal changes develop. Consequently there are additional questions to be answered regarding the effects of liming on higher trophic levels.

7.1.2. Ecosystem level research

There are major gaps in understanding the liming impact on estimating greenhouse gas (GHG) emissions for selected soil type, land use and management combinations. For example, there is a lack of field data from grasslands in the UK. The review by Kunhikrishnan et al. (2016) recommended that future GHG studies could address soil pH effects on N_2O fluxes, on the spatial distribution of N_2 and CH_4 at different scales and the interactive effect of lime with N fertilizers on GHG emissions. Linked to the dynamics of GHG there is a need for an improved understanding on the effect of liming on SOC stocks. Further research is required across a wide range of land uses and soil types as there are instances where liming has resulted in a C storage decrease (Paradelo et al., 2015), while elsewhere C storage has increased (Fornara et al., 2011). There is a need for work to better predict the net effects of liming, in terms of soil C gains or losses. Thus, for comprehensive understanding to develop, long-term field experimental sites are required. Likewise, long-term studies are required to better understand the impacts of liming on biodiversity because the detection of cascading effects between trophic levels can take time to develop.

There is a great need for improved understanding about the interaction of liming with other management practices which are implemented at a field scale. Indeed, the application of limestone is rarely if ever undertaken in isolation. Typically, liming will be just one of a suite of management practices and so it is important to know for which practices there is a significant interaction with liming. Liming interactions should be investigated with the major crop management practices such as crop rotation, crop variety, fertilizer and tillage. For instance, there is a great lack of UK or European studies on the effect of tillage practices on the lime requirement for arable crops. Because of the wide-ranging and significant impacts of liming on soils and crops, there is a great need for a thorough evaluation of how liming impacts ES. The development of trade-offs and synergies in ES after liming need to be investigated at an ecosystem level. This will enable the net impact from liming to be evaluated.

7.2. Implications of liming impacts on ecosystem services

Because liming impacts are far-reaching and significant on several ES (Fig. 5b) there is a need for policy to adequately account for the implications. Indeed in the past the UK government was strongly supportive of liming and up to 1977/78 there were subsidy payments provided for liming (MAFF, 1979). Recently, there has been less attention paid to liming and its multiple consequences in the UK. Future policy should consider the breadth of ES that are impacted by liming and recognise the interactions that can occur between ES. It is suggested that policy should focus upon ES impacts in terms of specific end effects rather than intermediate type or process effects which are often dynamic and highly variable. For example, it would be best not to focus on selected ES from nutrient cycling (a supporting service), but instead pay more attention to an ES for soil or water quality. To assess lime requirement, soil pH is the most common indicator used (Fig. 5); soil pH is also a simple and practical predictor of ES condition (Emmett et al., 2016).

In Fig. 5 the differences in lime-induced process change in soils, and thus crop responses, and ES are shown. The temporal scale, from rapid (short-term) to slow (longer-term) liming impacts, creates some difficulties in making future estimates on ES. Variation at spatial scale is not captured in Fig. 5, but is at least as great a challenge as that posed by the variation at temporal scale. The major drivers that operate spatially include: soil types, geology, farm management practices and land use type. To better understand the impact of liming on ES it is advised to better account for the variability in time and space. Because of the variable nature (in ES terms) of liming impacts it is necessary to identify where that liming results in positive ES outcomes, in contrast to negative outcomes. For example, a liming trade-off exists between increasing pasture production and increasing nitrate leaching (Holland et al., 2015). Therefore, whether for the land use on a mixed farm or across a whole landscape the same challenge still exists; that is to better understand where and when ES synergies or trade-offs from liming will develop? Information which answers these questions will be of great interest to policy makers.

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