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Nutrient stripping: the global disparity between food security and soil nutrient stocks

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Summary

1. The Green Revolution successfully increased food production but in doing so created a legacy of inherently leaky and unsustainable agricultural systems. Central to this are the problems of excessive nutrient mining. If agriculture is to balance the needs of food security with the delivery of other ecosystem services then current rates of soil nutrient stripping must be reduced and the use of synthetic fertilisers made more efficient.

2. We explore the global extent of the problem, with specific emphasis on the failure of macro-nutrient management (e.g. nitrogen, phosphorus) to deliver continued improvements in yield and the failure of agriculture to recognise the seriousness of micro-nutrient depletion (e.g. copper, zinc, selenium).

3. Nutrient removals associated with the relatively immature, nutrient-rich soils of the UK are contrasted with the mature, nutrient-poor soils of India gaining insight into the emerging issue of nutrient stripping and the long-term implications for human health and soil quality. Whilst nutrient deficiencies are rare in developed countries, micro-nutrient deficiencies are commonly increasing in developing countries. Increasing rates of micro-nutrient depletion are being inadvertently accomplished through increasing crop yield potential and nitrogen fertiliser applications.

4. Amongst other factors, the spatial disconnects caused by the segregation and industrialization of livestock systems, between rural areas (where food is produced) and urban areas (where food is consumed and human waste treated) are identified as a major constraint to sustainable nutrient recycling.

5. *Synthesis and applications.* This study advocates that agricultural sustainability can only be accomplished using a whole-systems approach that thoroughly considers nutrient stocks, removals, exports, and recycling. Society needs to socially and environmentally re-engineer agricultural systems at all scales. It is suggested that this will be best realised by national-scale initiatives. Failure to do so will lead to an inevitable and rapid decline in the delivery of provisioning services within agricultural systems.

Key-words: agro-ecosystem functioning, Green Revolution, intensification, provisioning, sustainability, wastewater, water quality

Introduction

Soil nutrient demand from crop production has greatly intensified as new high-yielding varieties have responded to the application of synthetic N, P and K fertilisers. However, the energy demand associated with the manufacture and use of fertilisers and long-term losses of macro- and micro-nutrients to the oceans, groundwater and atmosphere has led to increasing concern regarding the impact of nutrient resources on food security in developed and developing nations (Jones *et al*. 2012). Export of nutrient resources from soils of rural landscapes to feed increasing urban populations represents a significant impediment to achieving sustainable production in both developed and developing nations (Stoorvogel & Smaling 1990; Sheldrick, Syers & Lingard 2002; Sanchez 2006). Nutrient export from land, with no capacity to replenish those nutrients, represents a long-term stripping of soil stocks, exposing developing countries to significant long-term risk of soil productive failure (Stoorvogel & Smaling, 1990), and the associated health consequences. For example, approximately two billion people in the world are thought to suffer from at least one of the many forms of micro-nutrient malnutrition (WHO, 2007; FAO, 2009). Whilst such deficiencies tend to impact people in developing countries (Zhao & Shewry, 2011), for example zinc (Zn) in India, there are also important micro-nutrient shortages such as selenium (Se) in developed countries (Rayman, 2000). The socio-economic consequences of these deficiencies are substantial and widespread (WHO, 2002; The World Bank, 2006). Combating micro-nutrient deficiencies is considered by many to be a cost-effective intervention as measured by the Disability-Adjusted Life Years (DALY) averted and costs per DALY averted (Meenakshi *et al*., 2010). For instance, estimated annual disease burden of Zn deficiency in India is 2.8 million DALY lost, of which 2.7 million are due to mortality and 140,000 to morbidity, the majority of which are infants (Stein *et al*., 2007). Providing sufficient nutrients to the World's population is contingent upon national agricultural systems functioning efficiently.

In this paper the long-term depletion of nutrient resources at the regional and global scale is addressed and the implications of increasing nutrient demand on the long-term sustainability of soil resources, food security, rural economies, and the economies of developing countries is highlighted.

Agricultural provisioning and global nutrient systems in developed and developing countries

Global crop production provides food for expanding populations, but at a cost. Nutrient removal from soils of rural landscapes requires external inputs to balance export, and although N is often replenished (at a large energetic and environmental cost), other nutrients are not. Frequently, developing nations experience a net depletion in macro-nutrient stocks over time, whilst developed nations frequently apply excess amounts of N, P and K, inadvertently causing the excess mining of micro-nutrient resources (Sheldrick, Syers & Lingard, 2002). The application of high rates of N, P and K allow for increased production and extraction of resident soil nutrient stocks, however, N and P application, in excess of crop demands, can lead to profound environmental consequences (Galloway *et al*., 2004).

Over the past 200 years, global populations have become increasingly urban, shifting from 97% rural in 1800 to about 50% (75% in developed countries) in 2007 (United Nations, 2008). This shift to urbanization has meant that centres of nutrient demand have become increasingly geographically dislocated from the landscapes that supply soil nutrients. The disparity between soil-nutrient distribution and human nutrient-consumption patterns is illustrated by the harvesting of nutrients (in plant and animal products) across rural landscapes and their transport and concentration in urban environments. Enrichment of human sewage with nutrients necessitates substantial effort to isolate and remove these nutrients prior to delivery of the treated wastewater back to water bodies. In the absence of such effort, nutrients tend to be transformed into gases, diluted into rivers and marine bodies, and deposited in landfills. Only a fraction of these nutrients are re-cycled as industrial biosolids and ashes across rural soils leading to a slow depletion of soil nutrients (in particular trace elements) and carbon reserves (as a result of reduced primary productivity and below-ground C inputs), obligating the further mining of nutrients and the chemical production of N, P and K fertiliser to satisfy crop demands. In certain situations (e.g. N or P limitation), the mining of nutrients in an organic form can lead to the loss of organic matter which may have an overall detrimental effect on other aspects of soil quality (Emmett *et al*., 1997).

Nitrogen is only one of 14 mineral nutrients demanded by crops, indicating that Mg, Ca, P, K, S, and several micro-nutrients (Mn, Cu, Zn, Se) are also being exported from rural landscapes, often without adequate replenishment. Maize grain harvests in developed countries typically export around 0.22 kg Zn ha^{-1} (Hamilton, Westermann & James, 1993). One-hundred years of crop production has resulted in an estimated removal of over 20 kg of Zn ha^{-1} from landscapes which generally contain less than 250 kg total Zn ha^{-1} in surface soils (EA, 2007). These trace element removals represent an economic problem that can be addressed partially through fertilization programmes that include trace nutrient applications (Sanchez, 2006; Singh, 2009). Despite lower yields and nutrient off-take rates, however, asset stripping of soils in developing countries continues apace, as economic and logistical limitations do not allow for proper nutrient management plans.

Crop production has maintained pace with increasing population (1 billion in 1800 to 2.5 billion in 1950 (Goldewijk, 2001) to over 6.8 billion in 2009 (FAO, 2009)), but total land area in agricultural production has failed to keep pace with this (Fig. 2). Much of the increased productivity can be attributed to increased fertiliser production. Whilst N fertiliser consumption has increased massively from 5×10^6 t yr^{-1} in 1950 to 60×10^6 t yr^{-1} in 1980 to over 200×10^6 t yr^{-1} in 2009 (Smil, 2001), these trends are not matched in the use of other non-N fertilisers creating nutrient stock imbalance. Arguments for ignoring the impact of current agricultural practice on soil are often framed around food security ‘and the need to feed the world` (Nord, Andrews and Carlson, 2008). This contention is undermined by the fact that substantial areas of productive agricultural land are intended for non-food uses such as biofuels or inefficient use in livestock feed (Trostle, 2008).

The severity of nutrient stripping from agricultural soils is clearly dependent on the balance between inputs and outputs, which in turn is contingent upon several factors such as soil and crop type, management regime, climate and market forces. As these factors vary greatly around the world it is unsurprising that the degree of soil-asset stripping is not uniformly distributed at a geographical scale (Welch, Allaway & House, 1991). The issue is of greater significance in areas with older, highly weathered soils ($>10^6$ years old; e.g. Australia and SE Asia), in comparison to regions with relatively young soils created following disturbance (e.g. volcanism, glaciations; ca. 10^4–10^5 years old), such as those in Northern Europe and North America. The difference in nutrient baseline between these old and young soils is created by the slow but progressive leakage of base cations and P from ecosystems with age (Hedin, Vitousek & Matson, 2003). This leakage is counter-balanced by the gradual accumulation of Al, Fe, Si in soil minerals which provide little overall benefit to plants and typically exacerbate the problems of nutrient availability by binding up nutrients or releasing toxic elements (Kochian, Hoekenga & Piñeros, 2004). In the following section data is presented that contrasts these issues regarding nutrient off-take in the old soils of the developing world (India) with the relatively young soils of the developed world (UK). These countries are representative within their respective geographical areas.

Nutrient off-take in developing countries: India

In non-agricultural highly weathered systems, such as those of the tropics and sub-tropics, plants have evolved a range of strategies to minimize nutrient loss and maintain productivity (e.g. *in planta* recycling, symbiotic associations, slow growth), and thus nutrient stocks can remain close to steady state for centuries (Lambers *et al*., 2008). Conversion of this virgin land to agriculture represents the initiation of an inevitable and rapid decline in nutrient stocks. This is exacerbated by the fact that most crops, such as cereals, are rarely adapted to growing under low nutrient conditions and fail to yield economically without the addition of fertilisers (Wissuwa, Mazzola & Picard, 2009). Whilst economic yields can be sustained for short periods without fertiliser addition, productivity is fuelled partly by the mining of organic nutrients inducing a rapid decline in both the quantity and quality of soil organic matter (with obvious negative consequences beyond nutrient recycling such a loss in soil structure, reduced biological activity and water retention; Lal, 2004). In countries with highly weathered soils, the nutrient imbalance between crop off-take and replenishment from mineral weathering has attempted to be matched from the addition of NPK fertilisers. Current evidence suggests that the extent of the problem has seriously been underestimated and that NPK fertilisers have failed to effectively replenish mined soils with the wider range of nutrients removed during agricultural production.

The best example of this process can be found in India, the world's third largest producer and consumer of fertilisers (20.3 x 10^6 tons consumed per year of N, P_2O_5 and K_2O), which is exerting increasing pressures on its land resources (Singh *et al*., 2012). This pressure is driven by urbanization and the rapid population growth over the last 50 years. The Indian population is expected to reach 1.72 billion in 2060 (James, 2011). Furthermore, India has a high degree of social inequality which has resulted in widespread malnutrition, particularly in children (Subramanyam & Subramanian, 2011). For example, in 2004–2005 the demand for cereals was 193 × 10^6 t whilst in 2020–2021 the projected demand will be 262 × 10^6 t (Chand, 2007). To address the increased demand for food, agricultural reform programmes have doubled grain yields on irrigated land from 1.1 t ha^{-1} in 1960 to 2.5 t ha^{-1} in 2010. On balance, this looks like an agronomic success story (Lam, 2011). In reality, these yields remain far below their full potential and will remain so for the foreseeable future, notwithstanding the significant threat posed by climate change and declining P reserves (Manoj-Kumar, 2011). In India, at least 50% or more of recent increases in agricultural production are credited to fertilisers (Randhawa & Tandon, 1982). However, despite the increase in fertiliser applications, yields have continued to decline from 13.4 kg grain kg^{-1} nutrient in 1970 to 3.7 kg grain kg^{-1} nutrient in 2005 (Fig. 3; Samra & Sharma, 2009). In addition, the small gains in annual yield from fertilisers has come at a high environmental cost in terms of surface and ground water pollution by nitrates (Agrawal, Lunkad & Malkhed, 1999), enhanced N_2O emissions (Garg, Shukla & Kapshe, 2006), soil erosion (Manoj-Kumar, 2011) and a loss of soil carbon storage (Grace *et al.*, 2012). Unfortunately, there appears to be a sufficient lack of awareness amongst farmers that N and P additions alone cannot resolve the decline in soil fertility. India has suffered decades of K stripping from soil without replenishment inducing critically low levels and limiting production in many regions (Tandon & Tiwari, 2011). Moreover, stripping of the soil asset base is not limited to just the macro-nutrients. For example, based on several years of data and 250,000 samples, 40% of soils are now S deficient and 49% were found to be deficient in at least one micro-nutrient (33% in B, 12% in Fe, and less than 5% for Cu and Mn) (Singh, 2009). These other nutrient deficiencies typically go uncorrected and alongside water scarcity have dramatically reduced the efficiencies of N and P fertilisers. Even rectifying the K shortfall can achieve increases in N use efficiency of 10 to 90% (Brar *et al.*, 2011). This should not be seen as a static problem where the progressive stripping of nutrients has led to deficiencies becoming apparent at different times over the last 50 years suggesting the potential for new deficiencies to develop in the future (e.g. I, Cu, Mo, Co). The Indian experience demonstrates that balanced fertilization is a dynamic rather than a static concept as currently enshrined in a fixed NPK consumption ratio. As yield goals shift upwards, the "nutrient basket" demanded by these crops not only increases substantially, but also becomes more varied and complex (Tandon & Tiwari, 2011). Whilst crop diversification, integrated nutrient management and the use of legumes has been advocated as potential mitigation strategies (Shukla *et al*., 2010), this fails to holistically redress the nutrient deficit, or offers limited potential due to the lack of available resources (e.g. organic manures; Samra & Sharma, 2009) and the impact of increased urbanization on limiting nutrient recycling back to the fields. Scientific opinion is divided regarding the future of food security in countries such as India (Drechsel, Kunze & de Vries, 2001). Unless society can take action quickly and in a less polarised way, a very negative outcome seems more likely to prevail when current agricultural extension mechanisms and the soil nutrient stock deficit are considered.

Nutrient off-take in developed countries: the United Kingdom

In developed countries such as the UK, the baseline nutrient stocks in the relatively young soils is much greater but nutrient imbalances still occur in both macro-nutrients and micro-nutrients. Regional differences in climate and soil quality have been intrinsically used to maximise agricultural output; for example wheat yields have increased from 2 to 10 t ha^{-1} over the last 50 years due to inputs of nutrients and other chemicals (Dungait *et al*., 2012), but are now plateauing. The intensification of UK agriculture has also geographically separated farming systems: grass-based livestock farming is concentrated in the west of the country and arable farming, along with pig and poultry enterprises, is largely concentrated in the east of the country. Further nutrient segregation occurs between the rural areas of food production and urban centres of food consumption, with over 80% of the UK population living in large towns and cities. This segregation and urbanisation has led to a number of unforeseen consequences that have accelerated environmental pollution and may ultimately limit land use capability through nutrient stripping posing a threat to future food security.

First, the opportunity to recycle manures from grassland areas to arable systems is lost causing an almost total dependence on large inputs of inorganic N, P and K fertilisers to meet crop nutrient demand. Currently, only ~30% of the cereal area receives any cattle manure (Defra, 2012). Bateman *et al*. (2011) calculated that an annual export of 2.8 million tonnes of manure must take place from west to east to balance the supply and demand of

P. Much of this manure would need to be stored to enable it to be applied at convenient times during the crop growth cycle. This represents a major obstacle to sustainable nutrient use.

Second, the intensification of livestock systems and the general lack of manure export off the farm have led to large nutrient surpluses of N and P in the livestock sector and increased rates of nutrient leaching to ground waters and nutrient loss from agricultural land to surface waters (Edwards and Withers, 1998). Although annual nutrient surpluses in the UK are declining due to falling stocking rates and reductions in fertiliser use, the build-up of surplus P in the environment has left a legacy of stored P that will continue to pose environmental problems for decades to come (Jarvie *et al*., 2012). As pointed out by Schipanski & Bennett (2012), this is a global problem, affecting countries in different ways depending on whether they are net exporters or net importers of nutrients.

Third, increased urbanisation and modern patterns of food and water consumption have increased the flow of nutrients from rural areas to urban centres and historically very little of these nutrients have been recycled back to agricultural land. Recent budget calculations for the UK show that 539 × 10^3 t of N and 99 × 10^3 t of P were removed from arable areas in 2009, although more than 50% of this is fed back to livestock (Defra, 2010b). Although the amounts of biosolids and household food waste that are being recycled to land are now increasing, the amount of nutrients returned from urban centres to agricultural land remains low. For example, the proportion of total biosolid production (equivalent to 59 × 10^3 t N and 45 × 10^3 t of P) recycled to land has increased from ca. 40% in the 1980s to nearly 80% in 2010, but only about 2% of the agricultural area receives biosolids because of the logistics and costs of transport; negative farmer perception; and supermarket bans on application to some cropping systems (e.g. horticulture) (Davis, 1989). Approximately 96% of the UK population are connected to the public sewerage system and estimates show that ~184 × 10^3 t of N (England and Wales) and 43 × 10^3 t of P (Great Britain) are discharged from sewage treatment works into rivers each year (White & Hammond, 2009). This is not only a near permanent loss of nutrients to the oceans but is also a major cause of degradation of water quality and the ecosystem services they provide across much of the developed world.

Finally, concerns over nutrient imbalance caused by the specialisation of agricultural systems have centred on N and P because of the environmental problems associated with the loss of these nutrients to water and air. The impacts on trace element cycling have been largely ignored, most probably because of the perception that the majority of UK soils have plentiful trace elements for crop uptake because they are young. Soils in the UK that have naturally low levels of trace elements are well known (e.g. Mn, Cu, B, Co), and restricted to relatively small areas of very sandy or peaty soils, especially if they have been over-limed (MAFF, 1981; Sinclair & Edwards, 2008). Transient trace element deficiencies occur on a much wider range of soil types where crop rooting systems are restricted due to soil compaction, or do not have good contact with the soil; for example due to frost heave or where the seedbed has not been sufficiently consolidated at sowing (e.g. Mn deficiency).

In contrast to the resource-poor farmers of India, the socioeconomic infrastructure of resource-rich countries like the UK allows the redress of trace element deficiencies. However, current advice based on extensive field trials has always been to treat only susceptible crops on susceptible soil types when there is a known history of trace element problems, or where there are visible symptoms of deficiency that have been confirmed by soil and/or plant analysis (Defra, 2010a). This approach does not allow for ‘hidden or sub-clinical deficiencies’ that may be limiting crop yields or livestock health without visible symptoms occurring (Fisher, 2004), nor does it cater for emerging trace element shortages in crops that have hitherto not been considered susceptible. For example, our calculations suggest that the magnitude of the soil micro-nutrient deficit in the UK has increased over time as more N-responsive and higher yielding crops have removed more elements (Fig. 1 and see Appendix S1 in Supporting Information).

Until recently, there has been a lack of investment in field-based research to investigate these trends or to develop improved methods of diagnosis and treatment. A recent industry-funded research project investigating the effect of Cu, Mn and Zn on wheat yields has not yet found any evidence to support an increased occurrence of these deficiencies in the UK (HGCA, 2011). However, a comparison of the soil Cu, Mn and Zn concentrations in arable fields sampled in 2009–2010 with those sampled 30 years ago did show a consistent reduction in trace element content. Median concentrations of Cu, Zn and Mn reduced from 4.9 to 3.5 mg kg^{-1}, from 4.6 to 3.6 mg kg^{-1} and from 114 to 70 mg kg^{-1}, respectively (HGCA, 2011). The data suggests that UK soils are becoming depleted in essential trace elements, although not yet to a level that is causing yield limitation.

In some regions of the UK, more extreme mining of the soil resource is taking place, exemplifying the short-term economic gains that can be made at the expense of long-term sustainability. This is particularly acute on artificially drained organic soils (>2 m deep histosols) which have been converted for intensive horticultural production over the last 50 years and which are extremely high yielding and responsible for a large proportion of the UK field-grown horticulture sector (Hutchinson, 1980). These high rates of primary production are sustained primarily by tillage which promotes mineralization of the peat and the release of large amounts of nutrients (Höper, 2002). Consequently, microbial mineralization has converted a section of the landscape, which was previously a biodiversity hotspot and important for C sequestration, into a major source of greenhouse gas emissions with soil loss rates of ca. 1 cm depth per year. The ecosystem service trade-off between food security and climate change mitigation in this situation appears stark even before considering the intrinsic inefficiencies of horticultural production (e.g. high levels of wastage before and after reaching market).

Current outlook and the way forward

The long-term impact of nutrient removal without replenishment compromises our soil's natural capital and the provisioning services that are essential to maintain food security. A more holistic, sustainable, whole-systems approach to nutrient management is required that takes account of (a) the soil macro- and micro-nutrient stores available, (b) nutrient removal rates by different crop and livestock farming systems at different scales, and (c) rates of replenishment via fertilisers and opportunities to recycle and re-use exported nutrients within the food chain. Designing such an approach for more sustainable nutrient use along the whole food/feed/non-food chain requires a systemic, quantitative and dynamic approach to nutrient budgeting at regional, national and global scales and maximising opportunities for integration of crop and livestock systems and reducing wastage. Substance flow analysis (SFA; e.g. Sheldrick, Syers & Lingard, 2002) provides a quantitative framework for achieving this but requires basic information on nutrient stocks and flows which is not always easy to obtain.

Opportunities for recycling and recovery of nutrients along threshold leakage points in the food/feed/non-food chain might be expected to include inter-farm transfers of livestock manures, collection and/or recycling of food waste and wastewater sludges (biosolids), industrial-scale recovery of nutrients from large livestock holdings (e.g. pigs and poultry) and sewage treatment works and biological recovery of nutrients from surface waters (Smit *et al*., 2009). However, the cost of recovery, and logistics of transporting bulky organic materials even over modest distances is often prohibitive (Freeze & Sommerfeldt, 1985). New more cost-effective and innovative technologies are required to convert the nutrients contained in bulky organic wastes and wastewater into transportable fertilisers.

Sustainable approaches to nutrient use need to encompass an underlying principle that dependence on inorganic fertilisers is reduced, especially for nutrients such as P that might deplete quite quickly and for those that cause environmental damage. Whilst it is generally accepted that inorganic fertilisers are required to maximise productivity, attempts to better understand and enhance nutrient use efficiency and the biological contribution to crop nutrient uptake are now emerging (Dungait *et al*., 2012). Such approaches must still be tempered by the need to avoid over-exploitation of soil nutrient resources. Similarly, our current understanding of crop nutrient demand needs to be re-examined to assess to what extent nutrient requirements can be reduced through genetic engineering (e.g. low phytate grain; Raboy, 2009). Reducing crop nutrient demand without influencing crop yields or compromising nutritional quality and dietary intake will place less stress on soil ecosystems to meet that demand and result in the longer-term maintenance of soil provisioning services.

Due to our reliance on synthetic mineral fertilisers, intensive agriculture seems to have lost sight of how crops can acquire nutrients from their natural environment and how this can be used to the growers advantage. Similarly, the agricultural industry needs to harness the natural ability of soil organisms to aid in the delivery of nutrients at rates that match crop demand, thereby minimising losses. The difficulty in effectively managing soil microbial communities, however, should not be understated (Jones, Hodge & Kuzyakov, 2004). Further, microbially enhanced mineralization of organic compounds in agricultural soils may lead to the undesirable loss of soil organic C.

An ecosystems approach to the assessment of soil and landscape sustainability is increasingly being adopted by policy making bodies (e.g. UN, OECD and national governments) linking scientific research and decision making through valuation. This valuation is not necessarily monetary, and Edwards-Jones *et al.* (2000) argue that documenting ecosystem service values is useful because it (1) highlights the importance of ecosystem functioning for mankind, (2) highlights the specific importance of unseen, unattractive or unspectacular ecosystems, and (3) can aid in decision making and understanding the impacts of change.

The second of these can be very important for soils which are often overlooked. The ecosystems approach is not a solution, but offers a framework that is becoming widely understood and adopted by decision makers at a range of levels of policy development from local to global. One of the current drawbacks of the emphasis on ecosystem services is that it is focusing on 'final' goods and services. Consequently, planning decisions focused uniquely on final goods and service delivery is likely to overlook the health of the ecosystem service supply chain. This is important for issues such as nutrient stripping; policy makers must avoid trading off final goods and services such as crops, whilst neglecting the effects of crop production such as nutrient stripping. Delivering solutions and developing a sustainable future requires that agriculture accounts for the impact on final services of natural capital stocks from an ecosystem services approach (Robinson, Lebron & Vereecken, 2009).

Strategies for addressing soil micro-nutrient stripping and crop availability

Short term (1 year)

In the immediate short-term, farmers can correct for micro-nutrient deficiencies by using either soil or foliar applications (Table 1). Foliar applications offer the benefit of direct plant uptake to address deficiencies diagnosed within the growing season, whilst applications to soil are specifically required for those deficiencies that typically occur too late in the growing season to be treated (MAFF, 1981). Foliar applications are useful to either correct deficiencies or to supply crop requirements, where soil properties will result in immobilisation of the micro-nutrients if soil applied. Other potential delivery mechanisms to reduce the effect of soil immobilisation include the injection of micro-nutrients in solution into seed rows (Cartes *et al*., 2011), or soaking seeds in micro-nutrient solution prior to sowing (White & Broadley, 2009).

The above assumes the farmer/advisor/agronomist is sufficiently aware of the symptoms of micro-nutrient deficiencies in the crops they grow, has an understanding of the effects of micro-nutrient deficiency on macro-nutrient uptake, and is aware of the micro-nutrient demand for crops grown for a specific target yield. Seed suppliers, fertiliser companies and farming groups should ensure that up to date advice and guidance is delivered to the farming community.

Medium term (2–5 years)

During the slightly longer term, it is important for farmers to plan the strategy to rebuild the soil stocks of micro-nutrients, and restore balances (Table 1). Common practice is to continue cropping until deficiency symptoms are apparent, and then take action. However, a more holistic approach would be to encourage growers to adopt a strategy where soil micro-nutrient levels are restored to a sufficient level to adequately support crop yields (and quality) with regular soil applications.

Applications of organic resources can supply micro-nutrients to soil for crop uptake, and livestock manures represent a useful source. However, while manures supply a wide range of nutrients, knowledge of the content and availability of micro-nutrients from these sources is poorly understood. For example the UK Fertiliser Manual (RB209) (Defra, 2010) provides a wealth of information to farmers/advisors about the availability of N, P and K from a range of manure types (including the effects of timing and methods of applications to a range of soil types on N availability), but there is no information supplied about micro-nutrient content, let alone their availability. Sewage sludge is also a source of micro-nutrients, although in order to safeguard food quality (and human health), it is only applied to small land areas in the UK (ca. 2% of productive land), and specifically not to salad crops (ADAS, 2001). Indirect effects of organic resource applications can also enhance micro-nutrient availability in soils, e.g. through improved soil structure, increased soil moisture holding capacity, enhanced microbial activity and improved root development (Stevenson, 1991).

The application of livestock manures and other organic resources to arable land will only occur if the source of the organic resource is close enough. When this occurs on the same farm, then the advantages can be realised. However, the transportation of organic wastes from livestock systems which have become separated from arable systems, is not necessarily economically viable, and there are limitations to the land area on which organic resources can be spread (Nicholson *et al*., 2012). Any incentive which can help reconnect livestock and arable systems will not only benefit the micro-nutrient stocks of soils, but also offers a far more flexible strategy to the recycling of macro-nutrients and organic matter.

In the medium-term, the fertiliser industry could enhance the micro-nutrient content of its NPK fertilisers, as has been done in Finland with Se. In Finland, a minimum recommended Se target content of NPK fertilisers of 6 mg Se kg^{-1} NPK was set, to ensure that the Se requirement of crops are met, and that the macro-nutrients are used by plants efficiently (Varo, 1993).

Long term (> 5 years)

In the longer term, to address soil micro-nutrient mining and crop supply there is a need to integrate strategies for soil management and plant breeding and management (Table 1). Soil management strategies include the manipulation of soil pH to facilitate plant accessibility to micro-nutrients, the running down of high soil P index soils (through successive cropping and use of foliar applications of micro-nutrients), prevention of physical loss (e.g. via soil erosion), applications of micro-nutrients via foliar applications or to the soil in fertilisers or via organic amendments.

Plant breeding offers the opportunity to modify rhizosphere functioning and micro-nutrient root uptake. For example, deeper rooting plants could access micro-nutrients from deeper soil horizons (Kell, 2011), plants which exert effects on the rhizosphere pH could enhance localised pH conditions favouring root uptake, and enhanced mycorrhizal associations would increase the absorption area (Gao *et al*., 2007). Whilst investment in R&D in plant breeding to increase efficiency of uptake and storage of micro-nutrients in crops used for human and livestock consumption is to be encouraged, these breeding goals would still result in micro-nutrient mining if left unchecked.

Hence, integrated crop and soil monitoring and advice programmes should be developed. This would require an interdisciplinary approach with input from human nutritionists to set crop micro-nutrient standards and agronomists and soil scientists to a) test for plant and soil deficiencies, and establish agreed levels for critical crop values for remedying deficiencies, b) generate recommendations for soil micro-nutrient contents to satisfy crop demand at a given target crop yield, and c) provide advice in a similar way as is for macro-nutrients for optimal supply (of micro-nutrients) through inorganic fertilisers and organic resources. National programmes would need to take account of the range of soil types, cropping systems and climates – for example, although survey data suggest that on average India's soils are *ca*.30% deficient in B, the range is from 2% in alluvial soils to nearly 70% in the red soils of Bihar (Singh, 2008) with this range dependent on leaching from the soil profile in high rainfall areas, the organic carbon content of the soil (enhancing fixation of B in the soil) and the soil $CaCO_3$ content.

This section focused on mitigation for crop production; however, there is a deeper underlying issue that this does not address. The mining of micro-nutrients has largely unknown consequences for the multifunctional ecosystem service delivery of soils. The soil biota are well documented to be sensitive to excess of micro-nutrients and heavy metals and thus often used as an indicator of soil quality (He, Yang & Stoffella, 2005). Conversely, the consequences of depleting micro-nutrients on the soil biota and their functionality is not well documented but just as it affects NPP it is likely to adversely affect biogeochemical cycling and soil structure if higher fauna such as earthworms are adversely affected.

Conclusions

With a rising global human population, dwindling reserves of some mineral fertilisers (e.g. P) and in the face of huge environmental uncertainty from climate change, these are unprecedented times in terms of the need to balance food security without compromising the provision of other ecosystem services. This study has highlighted the magnitude of the problem and the huge challenge agriculture faces to devise and implement sustainable nutrient cycling in agronomic systems. Although technology brought about one successful Green Revolution in agriculture from 1950–1970, the systems agriculture created were inherently leaky and unsustainable from a nutrient perspective. If a continual depletion of nutrient stocks and increased nutrient poverty in both the developed and developing world is to be avoided, current production systems must be changed. A key question is therefore "how does society socially and environmentally re-engineer these systems at a local, national and global scale?" While some responsibility rests with individual farmers, it has to be recognised that this is a societal challenge that needs major international cooperation. As an intermediate solution, efforts should focus on national strategies to (1) close the nutrient cycling loop between rural producers and urban consumers, (2) promote greater recognition of soil-nutrient stock depletion (focusing on micro-nutrients as well as NPK) by industry and policymakers, (3) develop economically viable strategies for replacing lost micro-nutrient stocks, and (4) take an ecosystem services approach to the redesign of current food production systems.

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Supporting Information

Additional supporting information may be found in the online version of this article.

Fig. S1. Nutrient off-take of Manganese, Copper and Phosphate from wheat grain for harvest years 1969 and 2010 within England and Wales, sourced from June agricultural census data reported as a 5 x 5 km grid (EDINA agcensus).

Table 1. Comparison of wheat grain production area, yields and nutrient crop off-take values for 1968–1969 and 2009–2010. Source: MAFF (1971), Marks and Britton (1989)

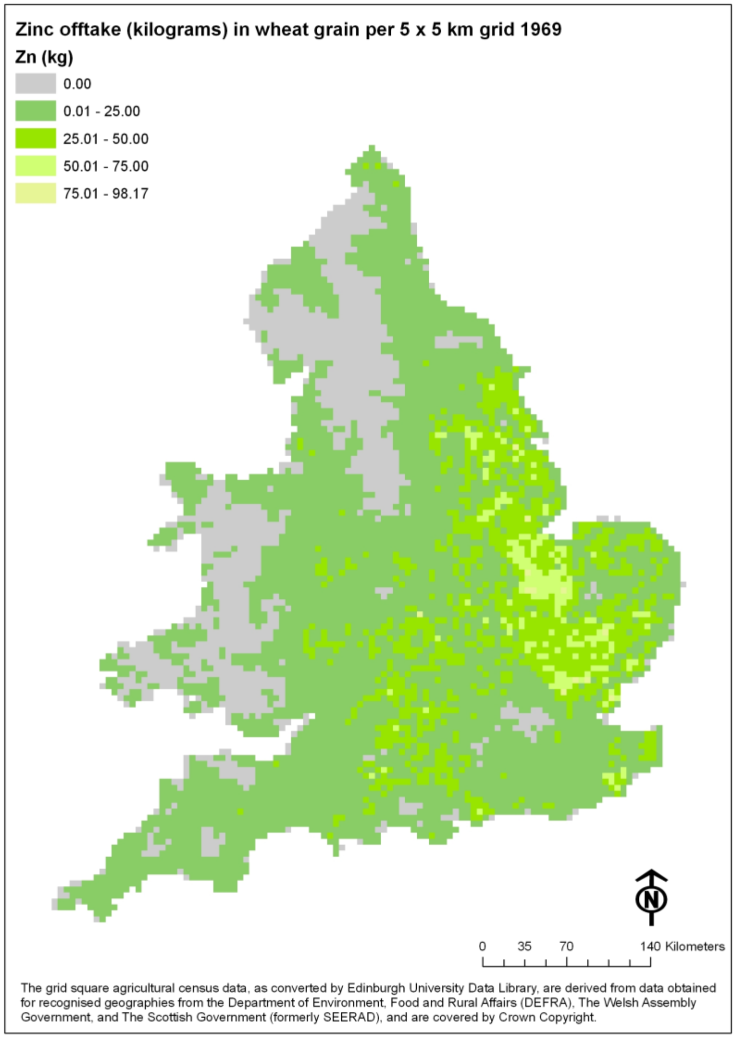
Region	Wheat area (000 ha)		Wheat production (000 t)		Cu off-take (kg)		Zn off-take (kg)		Mn off-take (kg)		P off-take (t)	
	1968/9	2009/10	1968/9	2009/10	1968/9	2009/10	1968/9	2009/10	1968/9	2009/10	1969	2010
England	933	1653	3284	13116	12738	51544	73031	295518	100772	407770	11323	45817
Wales	8	20	30	140	118	550	678	3154	935	4353	105	489
England & Wales	941	1673	3314	13256	12856	52094	73709	298673	101707	412122	11428	46306

Table 2. Mitigation strategies and future developments to mediate the loss of soil micro-nutrients (MN)

	Farm level (local)	Regional (national)	R&D requirement	Industry	Policy action/barriers
Short-term (seasonal)	Improved macro-nutrient use to enhance MN uptake Supplementary MN additions, in fertilisers and /or foliar applications Reduce P use on high index soils (as this locks up some MN) – use foliar applications of MN (when crops have sufficient foliar cover) whilst soil P levels are reduced over successive seasons Inject liquid MN into seed rows, coat seeds with MNs (Cartes *et al*., 2011), soak seeds in solution with MNs	Compilation of an inventory of total trace element usage in the UK to enable regional and national balance sheets	Determine the genetic and environmental variation in trace element uptake by different field crops to inform trace element budgets and scope the extent of trace element mining in UK soils	Development of improved guidance on diagnosis, prevention and treatment	Awareness within the fertiliser, crop breeding and farming sectors of importance of MNs in crop and livestock production systems
Medium-term (2-5 years)	Restoration of MN balances – often one application of Zn, Cu, Co & I is enough to restore soil levels for some time – but Se needs regular testing and application Increase mixed farming systems to reconnect MNs in livestock manures to arable land - rotations	Increase awareness Align livestock manure producers with cropland farmers to improve reconnection of MNs in manures to cropland soils	Improved knowledge of micronutrient content and availability from livestock manures, human manure, composts	Production of new fertiliser formulations – NPK fertilisers to include MNs such as Se (as is done in Finland), where a minimum Se content should be 6 mg Se/kg NPK Exploration of new sources of micronutrients Recycling of	Awareness, training, recommendations Incentives to increase use of livestock manures on arable land

				micronutrients from organic waste streams (e.g. waste water)	
Long-term (>5 years)	Use of new crop varieties with improved accessing and utilisation of MNs to increase MN content in crops for humans and livestock Regularly test soil and crops for MN content - dose soil with MNs every 5 years if required (according to Goodwin-Jones - more regular checks for Se). Finnish farmers have applied Se every year to solve their soil Se deficiencies		Plant breeding – improved uptake efficiencies (transporter cells, deeper rooting) Develop a system to advise on crop MN standards, and test for deficiencies – establish critical values which can operate as benchmarking within similar areas		Investment in R&D in plant breeding to increase efficiency of uptake and storage of MNs in crops used for human and livestock consumption Educate doctors, dieticians and health service about important of MNs in human diet for well-being – results in increased public awareness – creates demand for nutritious (adequate MN content) food and market for products

Figure. 1


Zinc offtake (kilograms) in wheat grain per 5 x 5 km grid 1969
Zn (kg)
0.00
0.01 - 25.00
25.01 - 50.00
50.01 - 75.00
75.01 - 98.17
0 35 70 140 Kilometers
The grid square agricultural census data, as converted by Edinburgh University Data Library, are derived from data obtained for recognised geographies from the Department of Environment, Food and Rural Affairs (DEFRA), The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), and are covered by Crown Copyright.

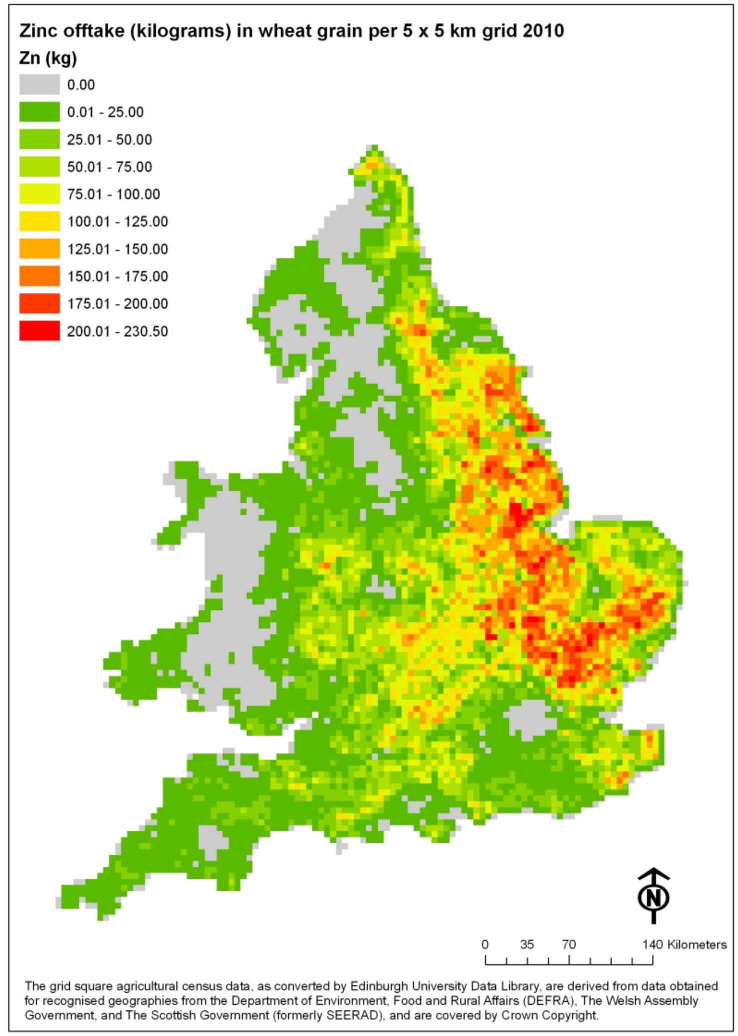
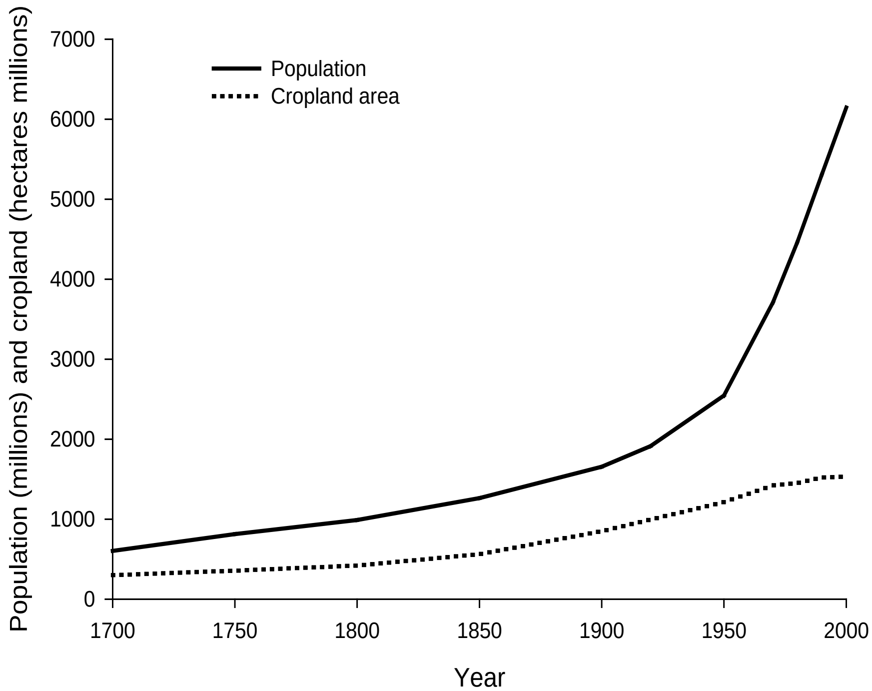
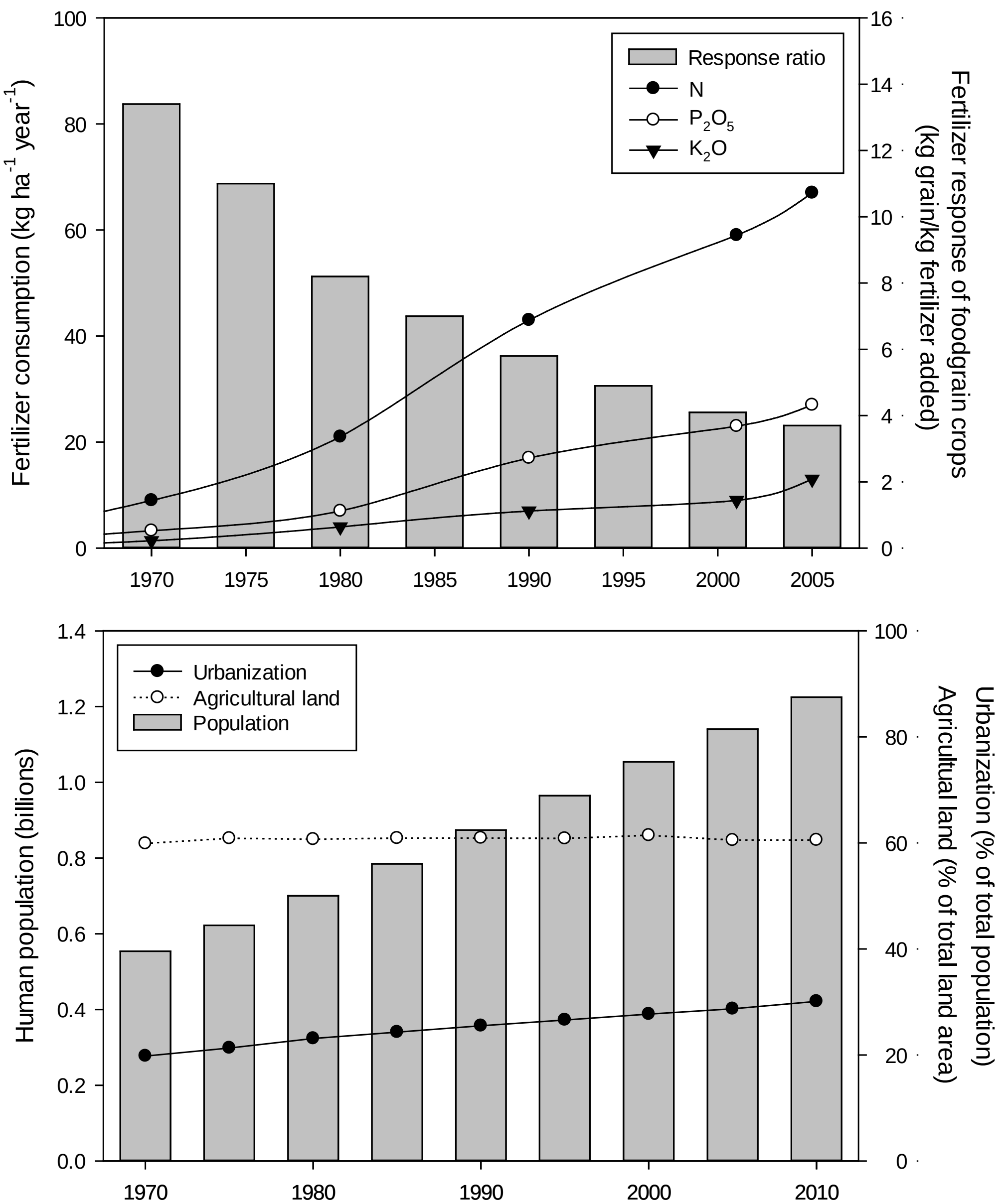

Zinc offtake (kilograms) in wheat grain per 5 x 5 km grid 2010
Zn (kg)
0.00
0.01 - 25.00
25.01 - 50.00
50.01 - 75.00
75.01 - 100.00
100.01 - 125.00
125.01 - 150.00
150.01 - 175.00
175.01 - 200.00
200.01 - 230.50
0 35 70 140 Kilometers
The grid square agricultural census data, as converted by Edinburgh University Data Library, are derived from data obtained for recognised geographies from the Department of Environment, Food and Rural Affairs (DEFRA), The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), and are covered by Crown Copyright.

Figure. 2

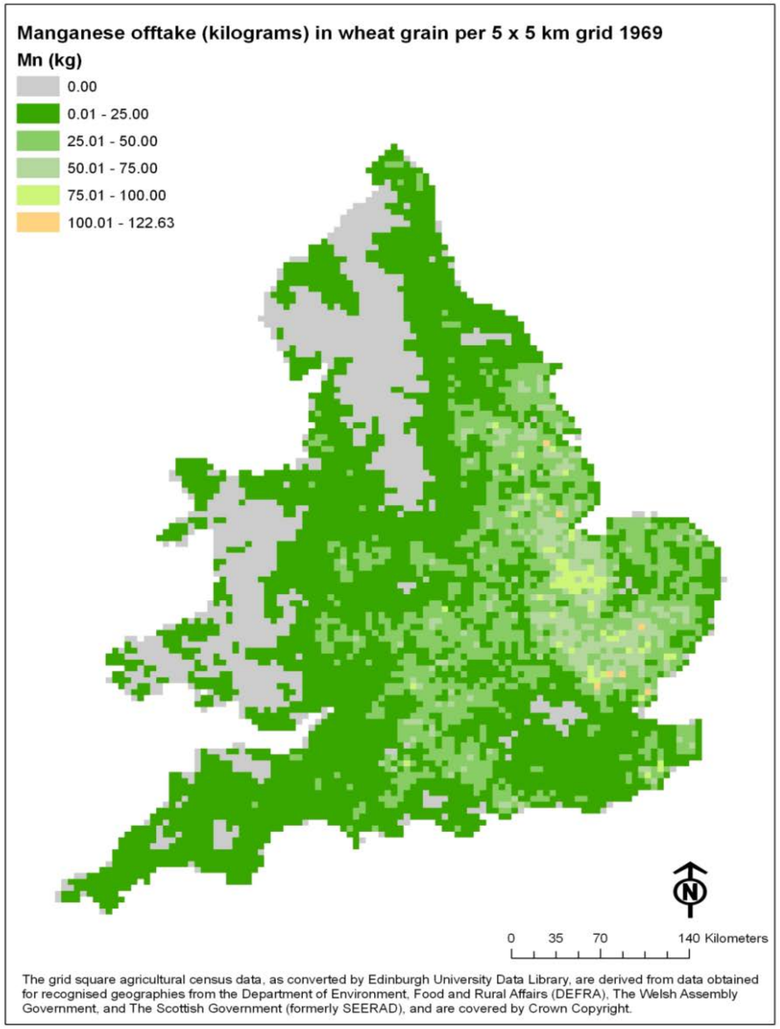


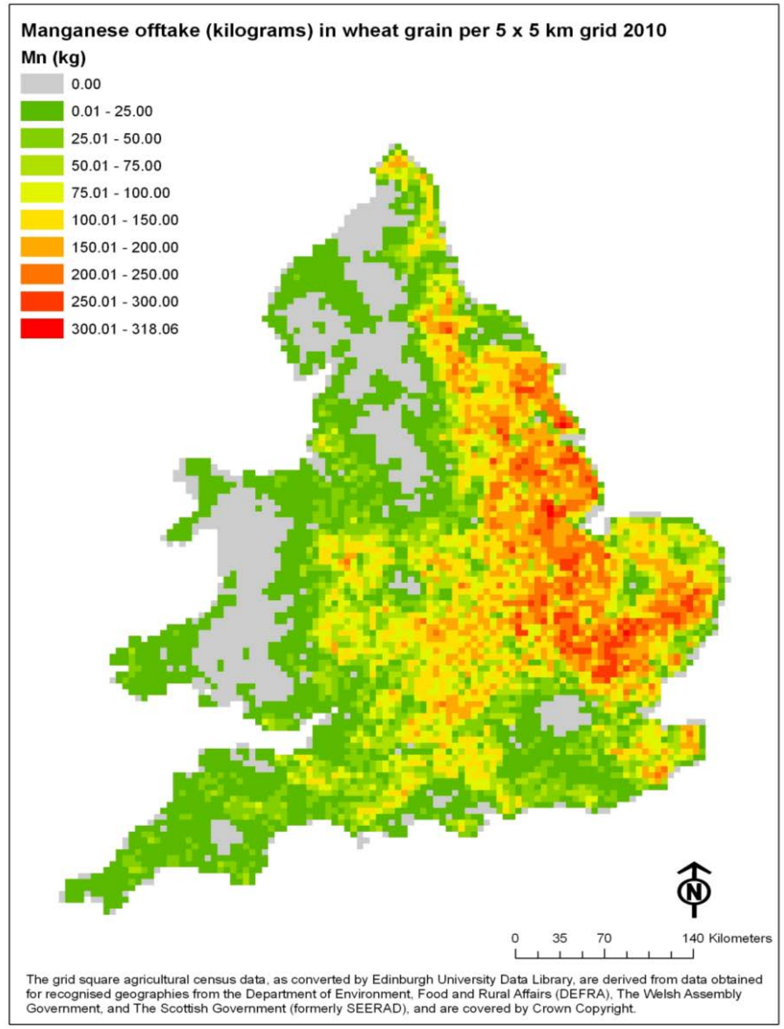
Population (millions) and cropland (hectares millions)
7000
6000
5000
4000
3000
2000
1000
0
Population
Cropland area
1700
1750
1800
1850
1900
1950
2000
Year

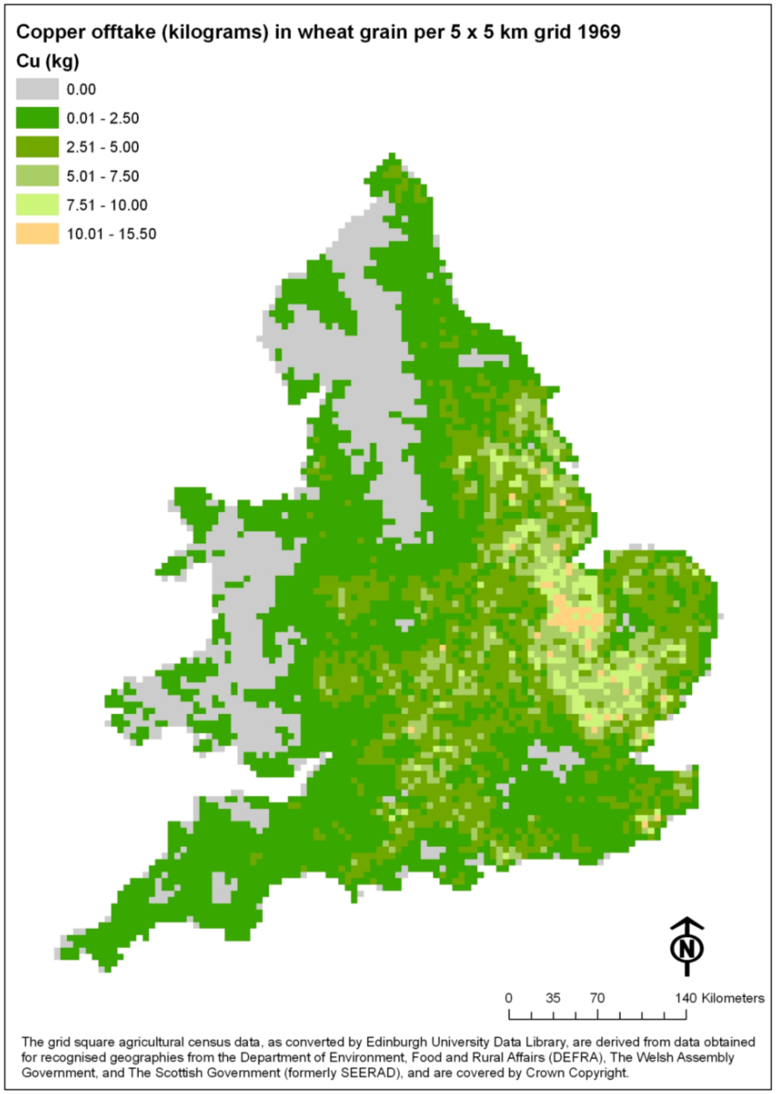
Figure. 3

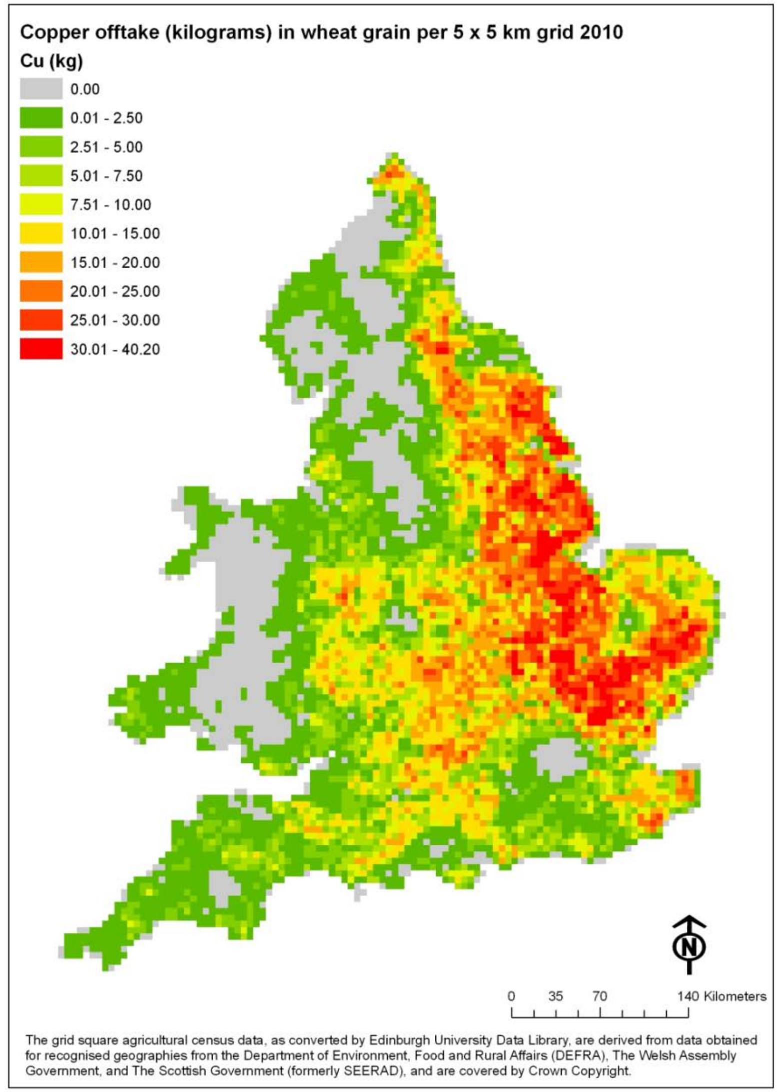


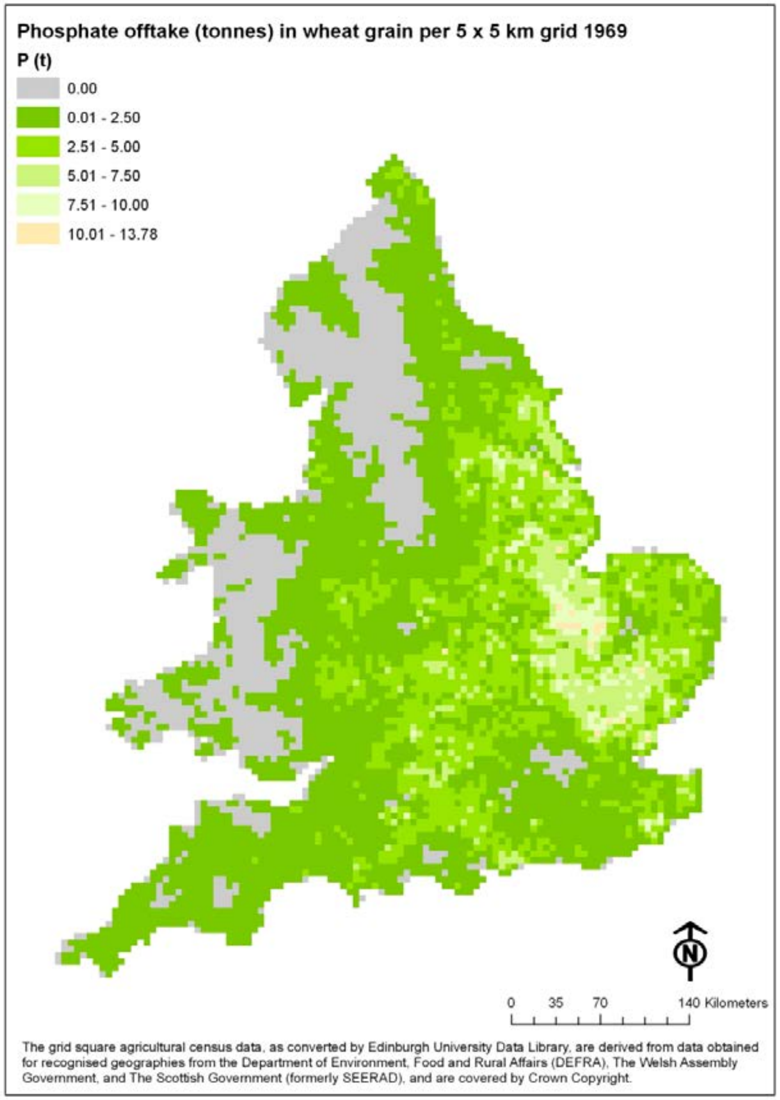
Fertilizer consumption (kg ha-1 year-1)
Fertilizer response of foodgrain crops (kg grain/kg fertilizer added)
Response ratio
N
P2O5
K2O
100
80
60
40
20
0
16
14
12
10
8
6
4
2
0
1970
1975
1980
1985
1990
1995
2000
2005
Human population (billions)
Urbanization (% of total population)
Agricultural land (% of total land area)
Urbanization
Agricultural land
Population
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
100
80
60
40
20
0
1970
1980
1990
2000
2010


Manganese offtake (kilograms) in wheat grain per 5 x 5 km grid 1969
Mn (kg)
0.00
0.01 - 25.00
25.01 - 50.00
50.01 - 75.00
75.01 - 100.00
100.01 - 122.63
0
35
70
140 Kilometers
N
The grid square agricultural census data, as converted by Edinburgh University Data Library, are derived from data obtained for recognised geographies from the Department of Environment, Food and Rural Affairs (DEFRA), The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), and are covered by Crown Copyright.


Manganese offtake (kilograms) in wheat grain per 5 x 5 km grid 2010
Mn (kg)
0.00
0.01 - 25.00
25.01 - 50.00
50.01 - 75.00
75.01 - 100.00
100.01 - 150.00
150.01 - 200.00
200.01 - 250.00
250.01 - 300.00
300.01 - 318.06
0
35
70
140 Kilometers
N
The grid square agricultural census data, as converted by Edinburgh University Data Library, are derived from data obtained for recognised geographies from the Department of Environment, Food and Rural Affairs (DEFRA), The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), and are covered by Crown Copyright.


Copper offtake (kilograms) in wheat grain per 5 x 5 km grid 1969
Cu (kg)
0.00
0.01 - 2.50
2.51 - 5.00
5.01 - 7.50
7.51 - 10.00
10.01 - 15.50
N
0
35
70
140 Kilometers
The grid square agricultural census data, as converted by Edinburgh University Data Library, are derived from data obtained for recognised geographies from the Department of Environment, Food and Rural Affairs (DEFRA), The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), and are covered by Crown Copyright.


Copper offtake (kilograms) in wheat grain per 5 x 5 km grid 2010
Cu (kg)
0.00
0.01 - 2.50
2.51 - 5.00
5.01 - 7.50
7.51 - 10.00
10.01 - 15.00
15.01 - 20.00
20.01 - 25.00
25.01 - 30.00
30.01 - 40.20
N
0
35
70
140 Kilometers
The grid square agricultural census data, as converted by Edinburgh University Data Library, are derived from data obtained for recognised geographies from the Department of Environment, Food and Rural Affairs (DEFRA), The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), and are covered by Crown Copyright.



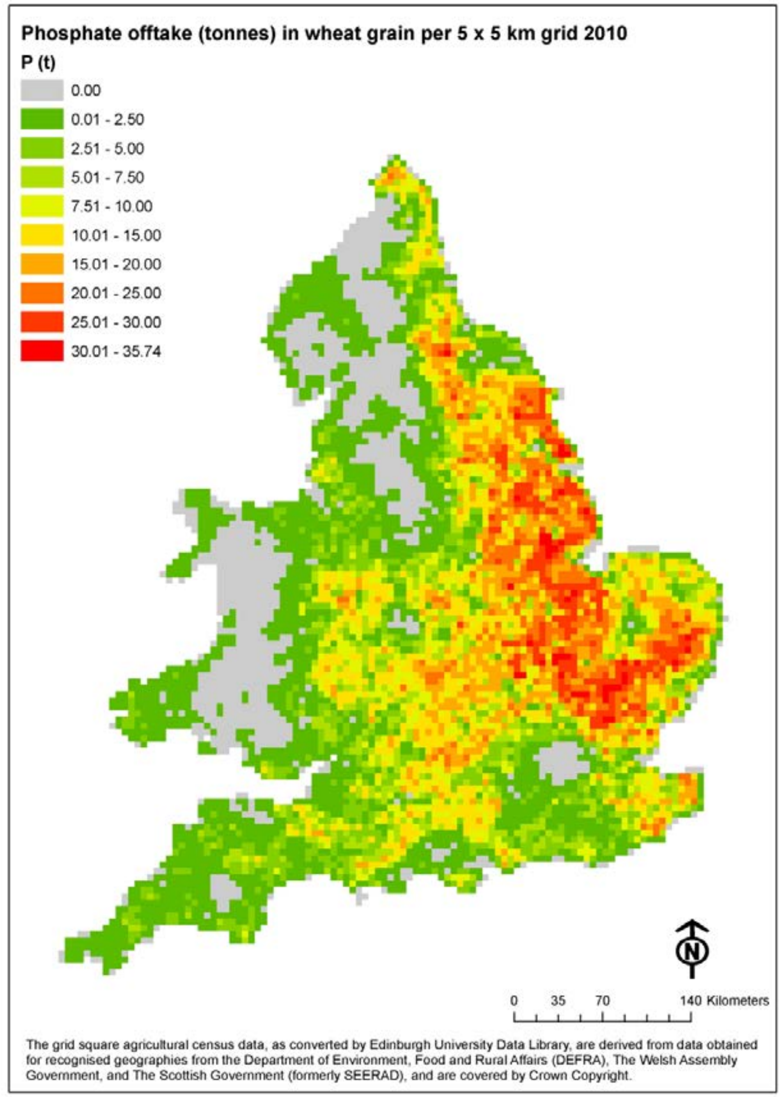


Figure S1. Nutrient off-take of Manganese, Copper and Phosphate from wheat grain for harvest years 1969 and 2010 within England and Wales, sourced from June agricultural census data reported as a 5 x 5 km grid (EDINA agcensus).