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Phosphate acceptance map: A novel approach to match phosphorus content of biosolids with land and crop requirements

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ABSTRACT

Phosphorus is a key irreplaceable nutrient that plays a major role in crop nutrition. The mineral form of phosphorus fertiliser is a mined resource and its supply comes predominantly from geopolitically sensitive parts of the world. A renewable source of phosphorus such as biosolids therefore offers a sustainable option. Nevertheless, continuous application of biosolids needs to be managed to ensure that soil is not saturated with nutrients which can then become a cause for concern in terms of enrichment of water bodies in the event of an erosion. Existing field trials have demonstrated the efficacy of biosolids as phosphorus fertiliser to meet crop demand whilst maintaining an environmentally safe amount in the soil. However, field trials are expensive, and an alternative would be a geospatial tool that builds on such information to act as a decision support tool to determine suitability of land to receive biosolids whilst ensuring that phosphorus levels are in environmentally safe limits.

Thus, a novel and evidence-based decision support method for assessing land suitability for biosolids application at a national scale known as the Phosphate Acceptance Map (PAM) is described here. It provides a sound basis for addressing this need, layering over the model the means to capture a range of realistic scenarios, developed with industry practitioners, to allow exploration of the consequences of different land management strategies. The research method has involved the development and application of a modelling approach for phosphate acceptance, drawing from a collation of the core geographical and descriptive data themes required. These data describe both the environmental characteristics of the land under assessment, as well as the expression of nominal stakeholder values and protected areas.

In considering the methods, it may be noted that the modelling drew upon key empirical data themes as a pragmatic approach. A number of key national datasets have been utilised such as the National Soil Map (Natmap), the 'National Soil Inventory' (NSI), geology and land use, as well as topography and prevailing climatic data. Demographic data was used to calculate potential arising nationally which was coupled together in the context of fertiliser recommendations. The issues addressed in the PAM modelling span borders and thus, where the data required is forthcoming, the methods demonstrated also have the potential to support wider application in other national contexts.

1. Introduction

Phosphorus (P) supply is a key macro nutrient for crops. The majority of P supply in agriculture in its mineral form is derived from phosphate rock. Approximately 40 million tons of phosphate rock (P_2O_5 equivalent) is mined annually, of which 80–90% is used in fertilisers (Defra, 2009). There is information on the global scarcity of P which has implications for food security (Cordell et al., 2009). The greatest reserve globally for phosphate rock is assigned to Morocco (Jasinski, 2011) and whilst reserves remain available, the cost of extraction is increasing, affecting fertiliser prices; volatility of supply for any reason could affect UK food security. A sustainable way forward will be to utilise renewable sources of P such as biosolids (also associated with increasing population), so reducing reliance on finite, mined rock phosphate.

The quantity of biosolids that is recycled to agriculture has increased since the implementation of various European directives, such as The Sewage Sludge Directive 86/278/EEC. In the UK, the GB Fertiliser Regulation is currently considering renewable sources of P, but discussions are still in their infancy. > 10 million tonnes (dry solids) of biosolids is now produced annually in the EU (Laturnus et al., 2007) and 12.8 million tonnes by 2020 (WRc (Water Research Centre),

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2010). The quantity of biosolids recycled to agriculture varies considerably between EU member states with the UK recycling approximately 80% (Smith, 2008).

The agricultural benefits of biosolids are widely recognised. However, application rates based on crop nitrogen requirements may lead to a build-up of soil P (Antille, 2011). A single application of dewatered biosolids will supply adequate phosphate for most 3–4 year crop rotations (Smith, 2008). Thereby application of phosphorus at rates greater than required by the crop represents a wasted resource and potential environmental hazard. More information is required regarding the long-term fate and release of P in biosolids treated agricultural soils to assess the efficiency of crop P utilisation (Smith, 2008). According to Cogger et al. (2013), repeated application of biosolids leads to accumulation of soil P when applied at rates to meet crop N needs. Previous work to-date on the nutrient value of biosolids has tended to concentrate on its value as a source of Nitrogen, with added phosphorus viewed as a "bonus". Loading soils with sufficient biosolids to meet the crop need for N will always over-apply P, which is not only inefficient and ineffective (economically and environmentally) but leads to an increased risk of leaching and eutrophication of adjacent water bodies.

In the UK, there will be a continued supply of biosolids, rich in phosphorus (P) (up to 5% dry matter) (Antille et al., 2013a, 2013b). It is accepted that recycling provides a more advantageous outcome than landfill or incineration (close to 80% of biosolids are recycled to agriculture in the UK - Smith, 2008). Several field-scale studies on the efficacy of biosolids as a fertiliser (Deeks et al., 2013; Pawlett et al., 2015; Antille et al., 2017) have shown that P is available to crops without increasing the soil P index, at least in sandy loam soils established with grass and major combinable crops. Whilst this provides valuable data, the cost of these trials is expensive. Consequently, to balance cost implications of field trials but without compromising on the application of biosolids to land, a geospatial approach is sought that can assist land owners to target application of biosolids, whilst maintaining suitable soil phosphorus levels to meet crop demand.

One reported project using such a geospatial approach is the Geographical Information System (GIS)-based ALOWANCE model (Agricultural Landbank, Organic 'Waste', A National Capacity Estimator) (Nicholson et al., 2012). ALOWANCE models the agricultural value of Nitrogen, considering this input from all sources of organic material based on data from the agricultural census. Two versions are reported, a commercial and an open tool. Both the public and restricted versions of ALOWANCE operate on a 10 km^2 grid and, although it is noted that future versions may include models of phosphorus, this is currently included only as background information. ALOWANCE is used in the consultancy sector, particularly with a focus on the water utilities in the UK.

The objective of this paper is to utilise geospatial analysis building on experimental data and substantive national datasets using a Big Data approach to produce the Phosphate Acceptance Map (PAM) to assess land suitability to receive biosolids application without compromising soil P levels and crop needs. This work also covers aspects related to interaction with relevant stakeholders and their perception on the use of PAM.

2. Materials and methods

In this paper, biosolids refer to pelletised materials which are granular between 2 and 5 mm and have an addition of urea and potash as a source of nitrogen and potassium respectively to make a balanced

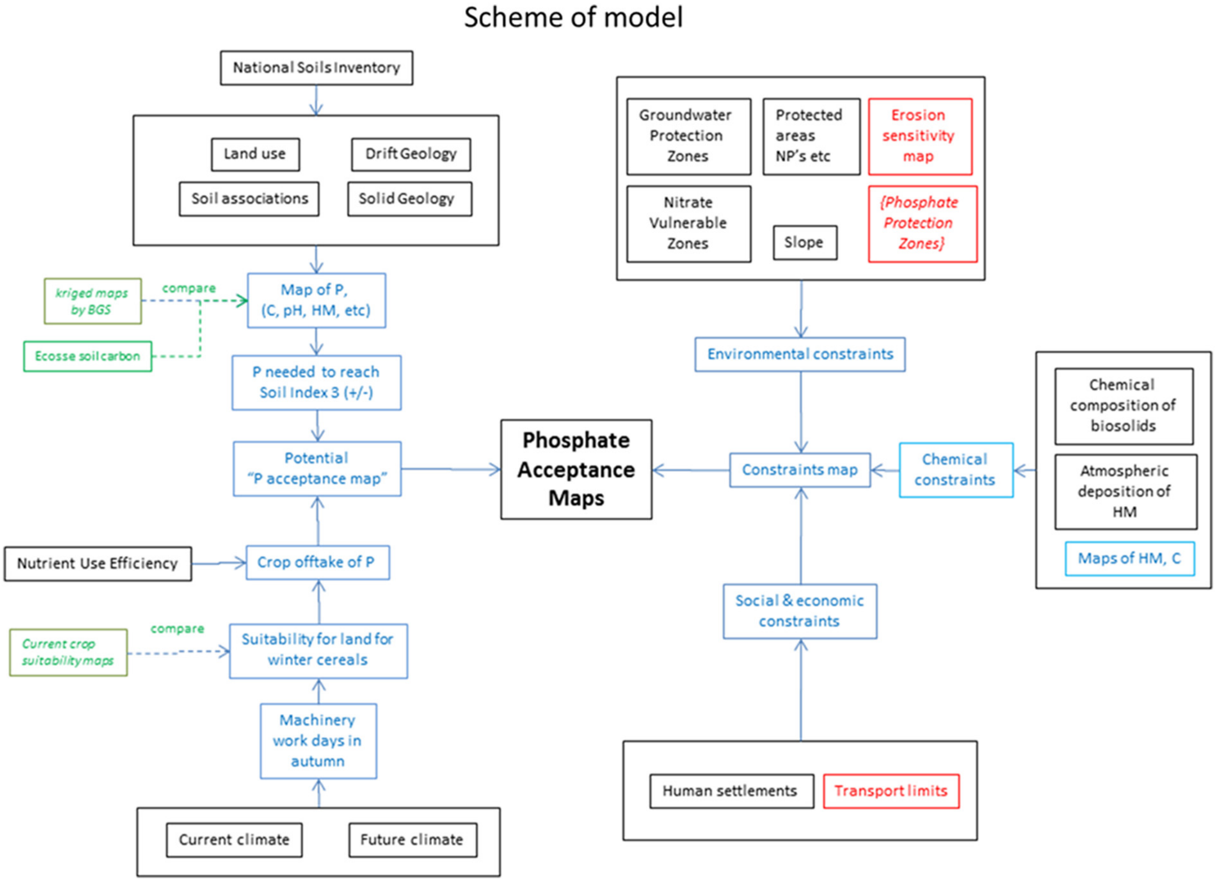


Fig. 1. Schematic of data flows in producing Phosphate Acceptance Maps. (Note, black outer text denotes specific data sources; red text denotes threshold limits; blue text denotes derivations made or modelling processes undertaken). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

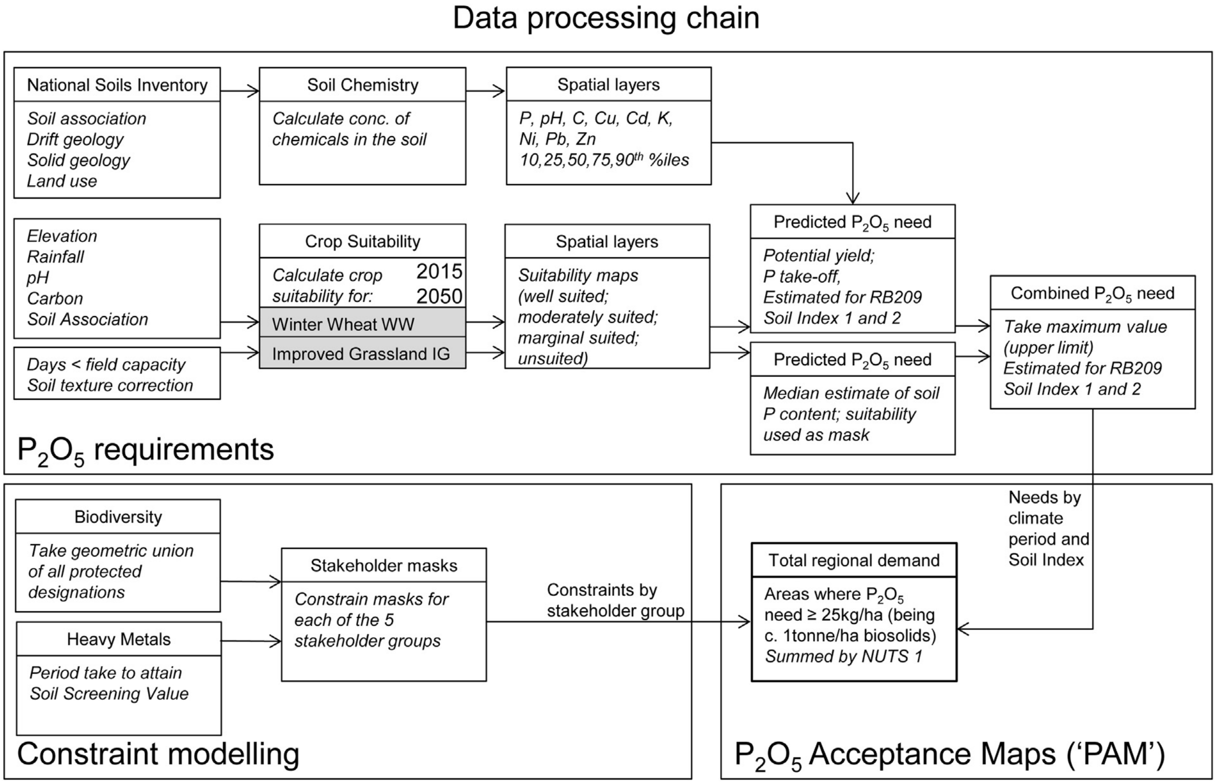


Fig. 2. Schematic of the data processing chain.

fertiliser. The phosphorus supply derives from the biosolids itself. However the use of the tool, Phosphate Acceptance Map can be adapted to biosolids on its own without additions of mineral nitrogen and phosphorus source.

The approach adopted in this work involves geospatial analysis and consultation with a target group of stakeholders. Consultation with the stakeholders highlighted constraints on the application of phosphate which includes a wide range of concerns such as eutrophication, efficacy as fertiliser and economics. Some of these concerns can be related directly to assessments drawn from existing datasets, e.g. the risk of erosion. Some concerns have good “proxy” values, e.g. land designated as being of special scientific interest, while many concerns cannot be easily modelled, e.g. customers' perceptions on the efficacy of biosolids. Fig. 1 provides a schematic illustration of the main flows of information within the modelling. Fig. 2 provides the details of the building blocks involved in data processing chain in formulating the PAM.

The PAM reported in this research by contrast, represents the first national spatial estimate of the requirements for P from two major crops under current and future (2050) conditions. PAMs are based on modelling the relationships with soil associations, solid and drift geology and land cover. Although each of these national data sets is expressed with slightly differing spatial structures, combining the processing results in maps having a nominal scale of 1:250,000. In practice, the smallest reliably identifiable unit is thus approximately 1 km^2, a one-hundred times improvement in the 10 km^2 resolution of ALOWANCE.

The geographical focus for this study was set as England and Wales. Handling of the substantial volume and variety of national-scale environmental and demographic ‘Big Data’ was facilitated by the processing capabilities of the Land Information System (LandIS) (Hallett et al., 2017; Keay et al., 2009; Hallett, 2017). The baseline information for agronomical trials and biosolids fertiliser efficiency was derived from published information such as Deeks et al. (2013) and Pawlett et al. (2015). Extrapolating from the field scale trials discussed in Deeks et al. (2013) and Pawlett et al. (2015) to the national contexts of England and Wales requires the integration of multiple large datasets

Table 1
Data sources utilised in the modelling.

Dataset	Source and description
Soil and crop parameters; levels of naturally occurring heavy metals in soil	Cranfield University's Land Information System (LandIS) (Hallett, 2017; Keay et al., 2009)
Crop variety and genetics	National Institute for Agricultural Botany (NIAB)
Solid and drift geology	British Geological Survey (BGS)
Land cover and atmospheric deposition of heavy metals	Centre for Ecology and Hydrology (CEH)
Human population and census demographics	National Statistics Office (NSO)
Agricultural economics	Farm Business Survey
Sites designated for biodiversity, landscape protection or sensitivity to pollution	Environment Agency; Natural England (NE); Defra
Climatological record projections	UKCP09
Characteristics of biosolids and long-term changes in soil conditions	Water utilities (United Utilities - UU)
Codes of Good Agricultural Practice and fertiliser recommendations	Defra; ADAS
The physics, chemistry, economics and socio-economics (stakeholder engagement) of biosolids use	Existing published papers and grey literature reports

(Table 1). The biosolids used in this study had a total P content of 5.86% (Deeks et al., 2013) and its bioavailability was sufficient to meet crop demand and did not increase soil P index. A more controlled study by Antille et al. (2014) as part of an incubation experiment using the same biosolids indicated that about 6.5% by weight was available over a period of 90 days.

Ultimately, the demand for P in agriculture is driven by crop requirements and how much is removed from the soil, for example in harvested grain, straw or silage. This is modified by the existing concentration of P in soils, with the target for arable crops being the mid-point of ‘Soil Index 2’ (20 mg/l P-Olsen) from the RB209 recommendations (Defra, 2010). The two crops considered in this model are winter wheat and improved grass. The rationale for selecting these crops follows previous work conducted applying biosolids involving these options. Furthermore, winter wheat and grass represent the combinable (annual) and perennial options of major crops grown in the United Kingdom.

In developing the PAMs, the following themes were incorporated within the methodology implemented, for estimating the need for P for winter wheat and improved grassland.

2.1. Crop need for phosphate

Arable land is categorised as; “well”, “moderately”, “marginally” or “unsuitable” for winter wheat. Suitability is primarily determined by the number of “working days” (for machinery) in the autumn. The rationale for restricting to only the working days is to ensure that trafficability of biosolids spreaders can be minimised on unsuitable soil conditions. A working day is defined as a day when the soil moisture content is below field capacity. Factors such as extreme stoniness, pH, slope, or risk of flooding, can affect suitability, but are not explicitly described. A correction factor based on the soil association is applied, increasing accessibility and hence suitability on freely draining sandy soils, but decreasing it on soils with high clay or organic matter levels. It is assumed that the soil target is ‘Soil Index 2’ (from the RB209 recommendations). Where the soil has a P index of 0 or 1, an additional 40 kg P_2O_5 is added, and where the index is 3 or greater, 40 kg is subtracted, so the maximum predicted application is 107 kg P_2O_5/ha/yr. (being land well suited to wheat with a soil index of < 2) to zero (being marginally suited land with a soil index > 2). Table 2 provides the data for winter wheat.

The assessment of suitability of land for improved grass is based on correlations between the existing distribution (estimated from the Centre for Ecology and Hydrology (CEH), 2007), soil type (soil association), soil chemistry (pH and Carbon), elevation and annual rainfall. Improved grassland is distinguished from semi-natural grasslands based on its higher productivity, lack of winter senescence and location and/or context. In some cases heavy grazing can cause misclassification with semi-natural grassland, or even arable land (Centre for Ecology and Hydrology (CEH), 2007). Raw data on pH, soil carbon, elevation and rainfall were gathered from Morton et al. (2011) and classified into various quantiles as shown in Table 3. Hence a “typical” (indicated as the 25%–75% quartile in Table 3) field of improved grass would have a pH of 5.94, soil organic carbon 3.65%, an elevation of 120 m, and annual rainfall of 888 mm; this land then being considered “well suited” for improved grassland. Conversely, land with a pH of < 5.5, and an elevation above 300 m, and with annual rainfall of > 1371 mm would be considered “marginal” for improved grass. Soil associations are ranked such that 95% of improved grass occurs on “suitable” soil associations.

Table 2
P_2O_5 requirements for winter wheat.

Suitability class	Work days	Yield t/ha	Annual need for P_2O_5
Well	> 80	8	67
Moderately	50 to 80	6	50
Marginal	20 to 50	4	34

Note: Annex 5 of RB209 (Defra, 2010) suggests 8.4 kg P_2O_5 removed per ton of wheat, assuming the straw is also removed.

Table 3
Environmental factors for improved grassland.

Quantile area of grass	pH	Soil carbon (%)	Elevation (m)	Rainfall (mm)
Lower 5%	≤5.5	≤3.1	≤3	≤603
5% to 25%	5.5–5.73	3.1–3.56	3–40	603–705
25% to 75%	5.73–6.15	3.56–3.74	40–200	705–1071
75% to 95%	6.15–6.65	3.74–4.50	200–302	1071–1371
Upper 5%	≥6.65	≥4.5	≥302	≥1371

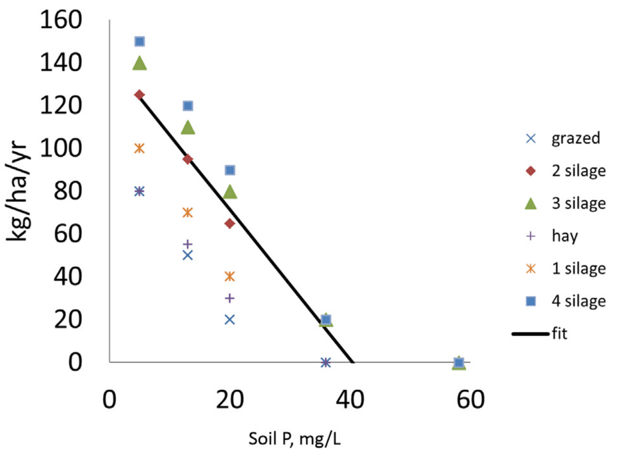


Fig. 3. Recommended applications of P_2O_5 kg/ha/yr. on grass.

Fig. 3 (using data from Table 4) shows the relationship between Phosphate fertiliser based on an area-weighted yield average of the RB209 recommendations (Defra, 2010) for hay and silage production (at 1, 2, 3 or 4 cuts *per* year) on soil with P index levels 0 to 4. P index 0, 1, 2 and 3 are indicated in the x-axis of Fig. 3 as 1–9, 10–15, 16–25, 26–45 and 46–70 respectively.

Relative areas of Hay and Silage are taken from the FBS (farm business survey) revealing that silage is over 80% of the improved grass area, and 2 or 3 cuts are more likely. This results in a simple linear regression equation for the annual P_2O_5 needed in relation to the soil P content as measured by Olsen P as shown in Eq. 1 which features in Fig. 3.

$$P_2O_5\ \text{requirement} = 141–3.49 \times \text{soil P} \tag{1}$$

Suitability for winter cereals and improved grassland is calculated under the current climate (Fig. 4) and with estimated values for 2050. Model estimates are the median values from 1000 iterations of the ITRC (UK Infrastructure Transitions Research Consortium) model, being a transient stochastic weather generator incorporating climate model uncertainty (Glenis et al., 2015; Pritchard et al., 2015), each iteration

Table 4
Recommended amount of P_2O_5 kg/ha/yr. on improved grass (RB209, 8th Edition).

P-Index (mg/L P)	Grazed	Hay	1st Cut	2nd Cut	3rd Cut	4th Cut
0 (1–9)	80	80	100	25	15	10
1 (10–15)	50	55	70	25	15	10
2 (16–25)	20	30	40	25	15	10
3 (26–45)	0	0	20	0	0	0
4 (46–70)	0	0	0	0	0	0

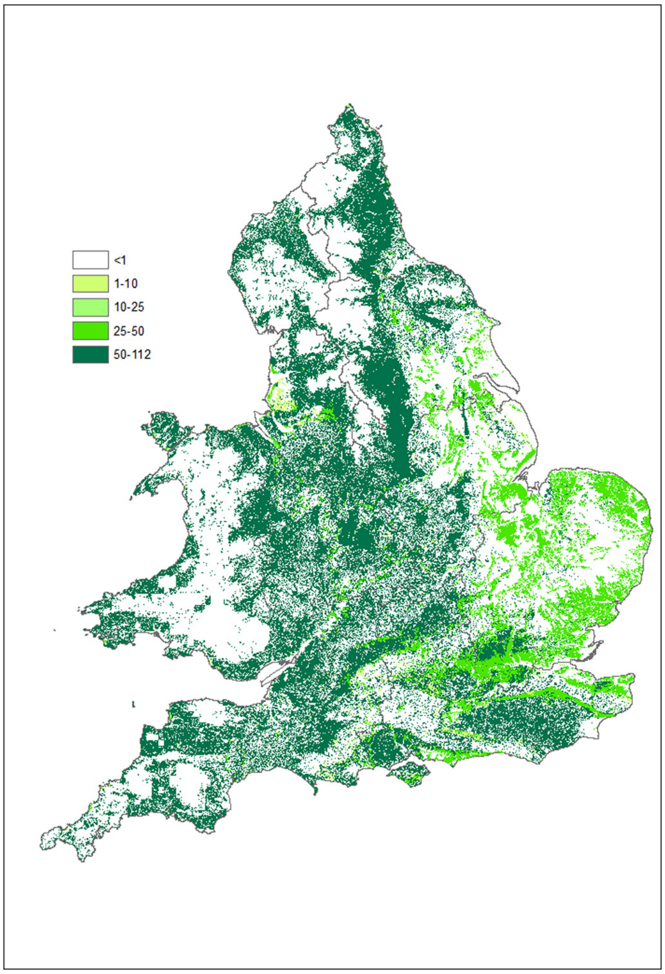


Fig. 4. Maximum amount of P_2O_5 (in kg/ha/yr.) for winter wheat and improved grass, under current climae, assuming a target soil concentration of Index 2.

consisting of 30 years of daily data. Changes in suitability are small over this period.

2.2. *Estimation of soil phosphate concentration*

Soil phosphate concentration is estimated using median regression of concentrations of P recorded in the NSI (National Soil Inventory) (Loveland, 1990; Cranfield University, 2017) against four categorical variables: soil association, solid and drift geology and land use. The same technique is used to predict pH, carbon content, and heavy metals. The NSI was conducted on a strict 5 km grid, the points being selected not to be "representative" of a landscape, but being based purely on their location. It is possible to apply geostatistical techniques such as kriging to such data sets, and these can produce smoothly varying surfaces. However, soil chemistry is dependent on factors such as land use and geology that are not smoothly variable. Therefore, instead of treating soil chemistry as an isolated phenomenon, a median regression approach was employed to relate soil chemistry to land use, solid and drift geology and soil association. Median regression was conducted using the function "rq" from the quantreg package in R (Koenker, 2015; R Core Team, 2014), whereby the probabilities that a class is statistically significant in the median regression is used as a "weight" when combining data from the four sources of data. For example, in landcover the "weight" given to "arable" is close to 1, but that given to "salt marsh" is close to 0. Similarly, in Drift Geology the weight given to RTDU (river terrace deposits) is much greater than that given to RMD (raised marine deposits).

2.3. *P budget during crop cycle*

The total demand for P represents the crop need, plus or minus the amount of P needed to maintain the soil at the mid-point of 'Soil Index 2' as recommended in RB209. There are a significant number of arable fields in East Anglia already well above the mid-point of Soil Index 2, so adding additional P would have little if any effect on their crop yield (a zero efficiency). However, in this case there might be an increased risk of eutrophication. The amount of fertiliser needed to change the soil index is very large compared to the annual crop needs, a value of 40 kg P_2O_5 is used to increase the soil concentration by 1 mg/l in Olsen-P.

2.4. *Constraints on the application of biosolids*

There are many potential constraints on the application of biosolids and these have been addressed across six themes. These constraints are important to consider as they provide limitations as to where biosolids can be applied and consequently a map that takes these into account provides the right information for the end-user about the actual available landbank.

2.4.1. *Erosion*

It is possible that applications of biosolids could help manage erosion through increasing soil aggregate cohesion or increasing surface roughness. However, best practice is to incorporate biosolids within the soil matrix, as leaving it on the surface could lead to very high pollution loads in sediment or in aerosol dust (leading to poor air quality). The default assumption is that areas with high rates of erosion should be avoided for biosolids application, where high is defined as being greater than the maximum estimated rate of soil formation (Verheijen et al., 2009). Erosion rates are taken from the Pan-European Soil Erosion Risk Assessment project (Pesera) (Kirby et al., 2004) and categorised into risk categories as shown in Table 5.

Using the soil formation rate as a guide to acceptable soil erosion rates in this way may be considered sufficient from an agronomic view (in maintaining the productivity of the soil), but may not satisfy other ecosystem services, e.g. the cultural value of archaeological sites, or the effects on water quality. The Soil Guide (Cranfield University, 2017) identifies 64 soil associations (out of 303 in England and Wales) as being particularly susceptible to water and/or wind erosion; these do not appear to be closely related to the areas of high erosion identified in Pesera. The lack of an obvious correlation between Pesera and the Soil Guide might indicate that farmers on sensitive soils do take more care to ensure vegetation cover at critical times of the year than do their neighbours.

2.4.2. *Biodiversity designations*

To account for biodiversity, five land designations (Sites of Special Scientific Interest SSSI, Local Nature Reserves LNR, National Nature Reserves NNR, Special Areas of Conservation SAC and Special Protected Areas SPA) have been amalgamated into a single "Protected Area - biodiversity" dataset. A single site may have multiple designations (for example, a NNR may contain a cluster of SSSIs). Depending on the legislation under which they are notified, (national or EU), different designations have slightly different levels of protection. However, no

Table 5
Rate of erosion and the use of biosolids.

Rate of erosion t/ha/yr.	Erosion Class	Constraint on application
≤0.3	Low	No
0.3 to 1.4	Moderate	No
≥1.4	High	Yes

weighting or ranking has been applied, thus land is either designated or not. SSSI and Natura 2000 sites (SAC & SPA) are specifically noted in the Code of Good Agricultural Practice as being potentially sensitive to pollution (Defra, 2009). Management of designated landscapes are strictly monitored and hence application of biosolids will be very limited due to potential pollution and nutrient enrichment.

2.4.3. Landscape designations

Three landscape designations were identified (Areas of Outstanding Natural Beauty AONB, Country Parks and National Parks), all amalgamated into a single “Protected Area - landscape” dataset. It is considered more likely that biosolids would be used in a landscape designated area than in a biodiversity designated area, as designated landscapes can include some areas of arable cropping.

2.4.4. Pollution designations

Four pollution designations were adopted (Nitrogen Vulnerable Zones NVZ, Nitrogen Sensitive Areas NSA, Environmentally Sensitive Areas ESA and Ground Water Vulnerability Zones GWVZ), all amalgamated to a single “Protected Area – pollution” dataset. NVZ cover virtually the whole of England making this a “blanket” prescription, the most important component of this category is the upper limit on the application of Nitrogen from all sources, being 250 kg/ha/yr. When applying biosolids, the N is added as a top-up since very little is inherently present it. This poses a risk of build-up of P when application are based on level of N. Periodic sampling of soil for P will ensure safe levels are being maintained.

2.4.5. Distance constraints

To add a distance constraint in area selection, the 2011 demographic census data was used to identify those settlements having > 100,000 people. This was used as a “proxy” measure for the location of sites producing biosolids. PAM users may specify a minimum buffer distance (by default 1 km) and a maximum transport distance (by default 25 km) from the settlements. The size threshold of 100,000 is consistent with the Urban Waste Water Treatment Directive that applies more stringent requirements on locations above this size. Areas identified in the census as urban are generally smaller than those areas masked out of the Pesera erosion estimates as urban; as a result, this can ocassionally create a small fringe effect around towns on some maps.

2.4.6. Heavy metal constraints

A heavy metal constraint was added as a simplistic estimate of the minimum time it would take for the concentration in the soil of one of five heavy metals (Cd, Cu, Ni, Pb, Zn) to exceed the relevant Soil Screening Value (SSV). A simple model approach starts with the current estimated concentration in soil and assumes that atmospheric deposition continues at its current rate (estimated for 2011 from the CEH rural network) and that biosolids are applied at a constant rate of 1 t/ha/yr (dry weight basis) with a typical concentration of heavy metals (being the median values derived from dataset provided by a regional water company in the UK) (Deeks et al., 2013; Pawlett et al., 2015). The PAM model does not account for losses arising due to leaching, crop removal or soil erosion, nor does it account for potential changes in soil pH: estimates are therefore better considered as a relative measure (or ranking) of sensitivity to heavy metals rather than an actual prediction. Values from the model are, however, concurrent with those reported by Nicholson et al. (2006) in an audit of all sources of heavy metals.

In addition to collating the datasets required and undertaking geostatistical analysis, two stakeholder workshops were organised whereby facilitated focused group discussions were held. Stakeholder workshop participants included water utility companies, farmers, landowners, agronomists, fertiliser companies, waste management organisations, agricultural trusts and associations, academics and regulators. Aubin et al. (2002) undertook an assessment of sludge disposal in the EU, identifying seven stakeholder groups and their major concerns, summarised in Table 6. The consultation with stakeholders was done a posteriori to validate the approach taken in this work. The selection of stakeholders was based on the supply chain from production of biosolids until its application to land and the related regulatory and commercial bodies involved in this process.

Table 6
Stakeholders and their concerns regarding biosolids (after Aubin et al., 2002).

Stakeholder group	Main concerns
Farmers	Access to cheap fertiliser Relationship with agri-food industry (main customers)
Agri-food (food industry and retailers)	Market and brands (perceived quality) Public health (perceived and real threats) Disposal of sludge produced by the food industry
Consumer groups	Food safety (perceived and real threats)
Land owners	Liability (if there is a public health issue) Land values (possible negative effect)
Communities	Economics (water bills) Public health (perceived and real threats) Nimbyism (‘not in my backyard’)
Nature protection	Usually only minor interest in agricultural systems
Water companies	Economics (minimising costs) Recycling

3. Results

The modelling has led to the production of a series of P acceptance maps, accommodating constraints arising through the perceived priorities associated with each of five nominal stakeholder groupings, outlined below.

3.1. Managing stakeholder priorities

Initial discussions with stakeholders identified a range of priorities and concerns. To seek to reflect this in the research, five nominal stakeholder groups were “modelled”, permitting a representation of the spread of perceived concerns. In practice, this proved a useful approach as, in subsequent stakeholder engagement exercises, stakeholders were invited to consider which viewpoint they felt most closely associated with – helping orientate a shared understanding of the issues of concern. One of the groups was held as representative of stakeholders who consider all constraints to be equally important, whilst the other four give respectively more weight in turn to types of pollution (affecting protected areas; exacerbating soil erosion; and increasing heavy metal application to soil), to biodiversity, or to economics (Table 7). Where an economic constraint was adopted, locations were identified within thresholds of 1 km of a city, or > 25 km from a city. The heavy metal constraint applies where the Soil Screening Value (SSV) will be reached within 100 years. In practice, it was found to be possible to scale constraints from ‘0–1’, whereas for clarity Table 7 identifies Boolean variables (* = yes/no). The constraints adopted are portrayed cartographically in Fig. 5-9.

3.2. P content in biosolids

Assuming the application of biosolids at rates of < 1 t/ha (dry weight) would be insufficient, a calculation may be undertaken to determine how much of the predicted demand for P_2O_5 (for winter cereals and improved grass) can be supplied by biosolids. Table 8 identifies how much of the demand for P_2O_5 can be satisfied by biosolids in each Local Government Region (NUTS1).

Ignoring London (italicised in Table 8), which has virtually no demand for Phosphate fertiliser within its boundary, it may be observed that in most cases, in most regions, biosolids can supply a useful

Table 7
Weightings used to model the concerns of the synthetic stakeholder groups.

Constraint	Stakeholder Group				
	1	2	3	4	5
Pollution – Protected Areas, e.g. NSA, ESA, etc.	*	*			
Pollution – Erosion rates – erosion greater than soil formation.	*		*		
Pollution – Heavy metals – time for Soil Screen Value to be reached.	*		*		
Biodiversity – Protected Areas e.g. SSSI, NNR, SAC, etc.	*			*	
Biodiversity – Protected Areas e.g. AONP, NP, etc.	*			*	
Economics – distance biosolids moved.	*				*

* Indicates the coverage of various constraints for a particular stakeholder group.

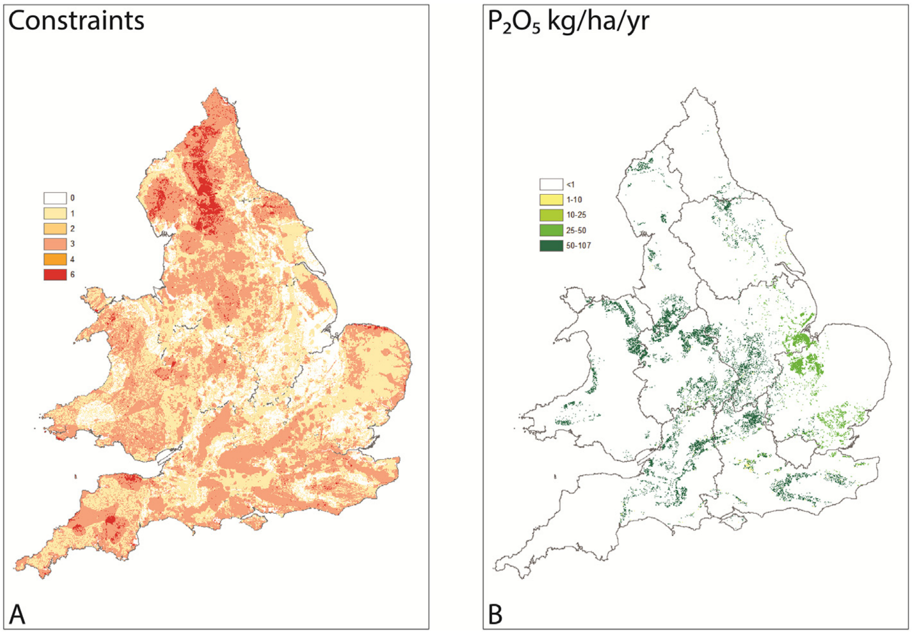


Fig. 5. Stakeholder Group 1 - All Constraints Applied (Note, No Location has exactly 5 constraints so omitted from legend).

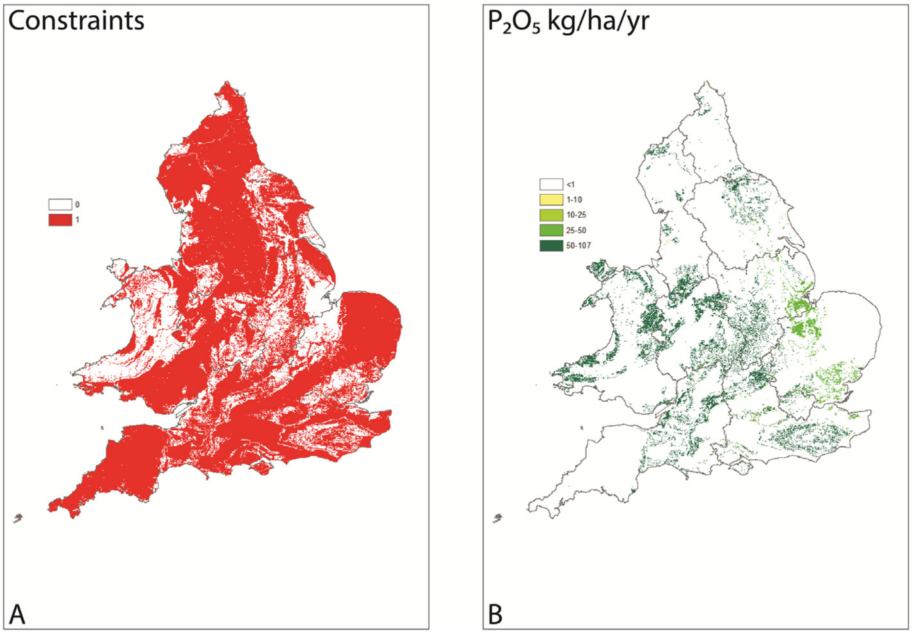


Fig. 6. Stakeholder Group 2 - Constrained By ESA, NSA, and Groundwater Protection Zones etc.

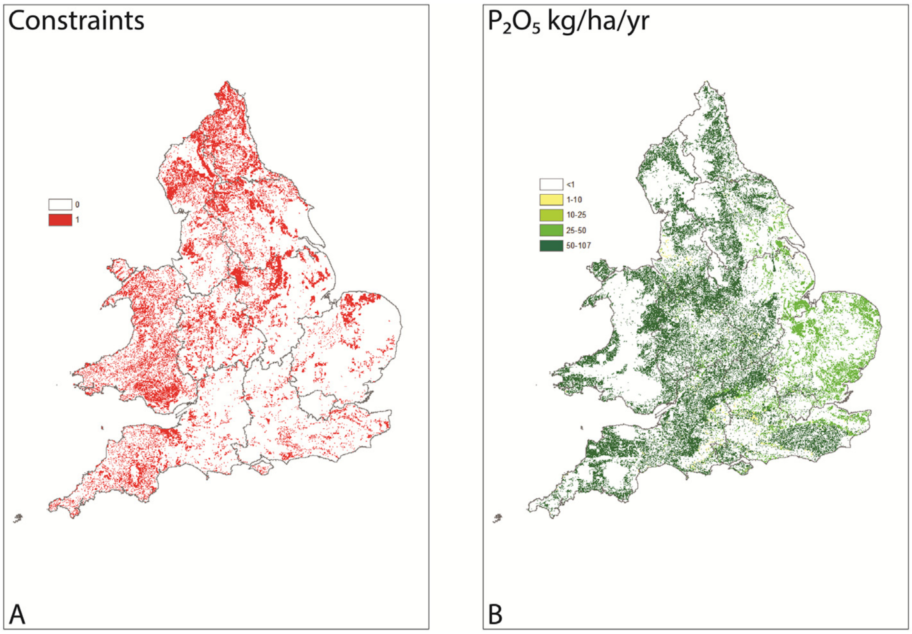


Fig. 7. Stakeholder Group 3 - Constrained by erosion and accumulation of heavy metals.

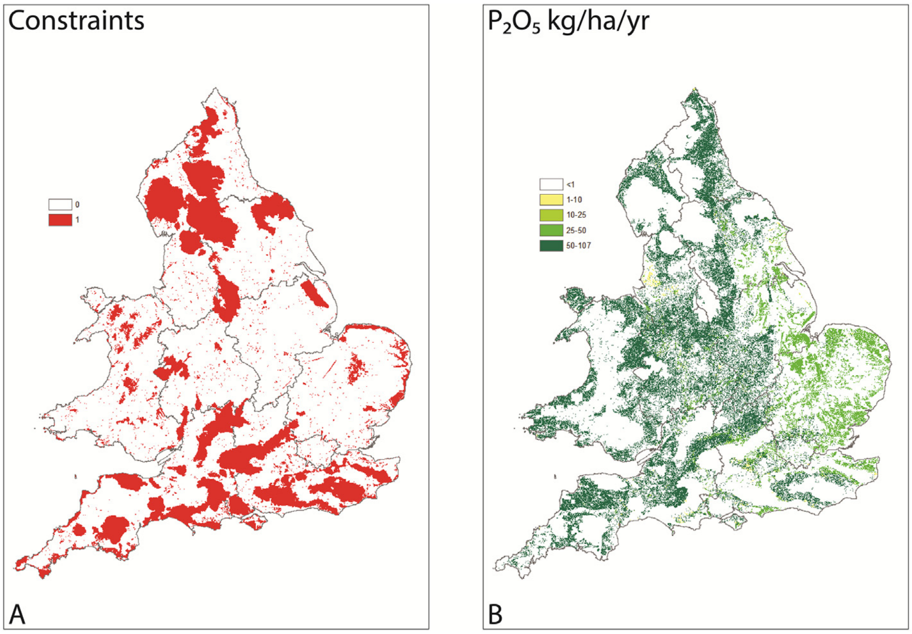


Fig. 8. Stakeholder Group 4 - Constrained by biodiversity zones (e.g. SSSI, NNR, national parks).

percentage of the demand for P_2O_5 without using more than half the wheat/grass landbank. The exception is Stakeholder Group 2; if the ESAs, NSAs and GPZs are viewed as absolute constraints on the application of biosolids, then four NUTS1 regions (North-East, North-West, Yorkshire and East-Anglia) have an oversupply of biosolids derived P fertiliser. Comparing the modelled results to those in the publically available versions of ALOWANCE (Nicholson et al., 2012) the PAMs reveal increased constraints on the landbank in East Anglia due to the high soil P index values, and a smaller available land bank in some of the wetter, western areas - due, perhaps to different definitions of what constitutes “improved” grassland.

The value as to how much landbank is required depends upon the strategy adopted for the application of biosolids; the two extremes are:

(i) Selection of land with the highest demand for P_2O_5 first to minimise the landbank;
(ii) Selection of land with the lowest demand for P_2O_5 first to maximise the area and minimise the load.

In practice the actual landbank will be somewhere between these extremes. Table 9, indicates the upper and lower limits nationally for each of the stakeholder groups.

Figs. 5–9 provide alternative realisations of the constraints adopted (panel ‘A’) for all stakeholder groups and locations where biosolids fertilisers are needed and can be applied (panel ‘B’).

Under the future climate (assumed conditions for 2050), the demand for fertiliser will change and the supply of biosolids will increase.

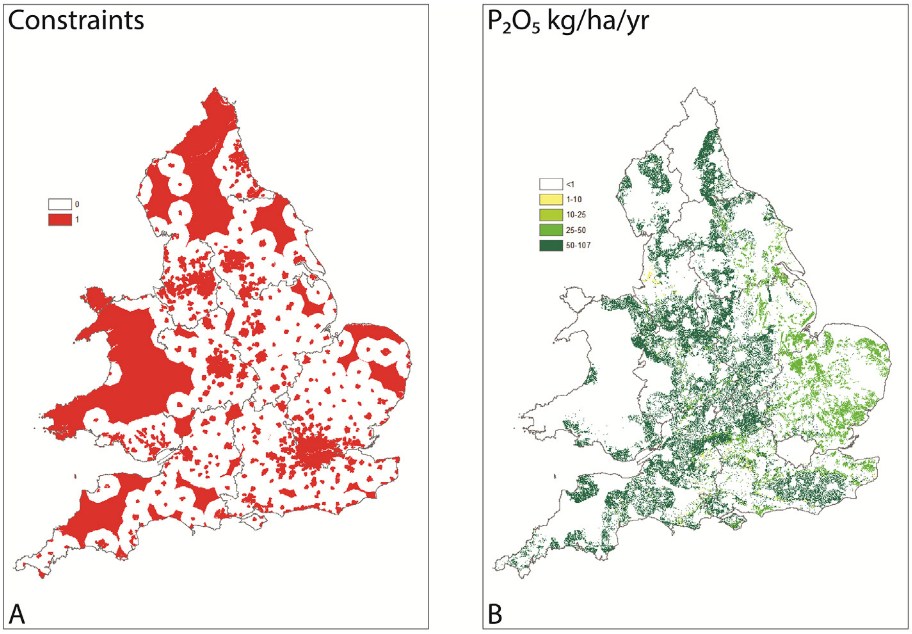


Fig. 9. Stakeholder Group 5 - Constrained by distance.

Furthermore, in all cases the increased supply of biosolids (assuming supply grows directly in proportion to the predicted increase in human population), will be greater than the predicted increased demand for P, however, these differences are considered minor.

3.3. Development of the PAM tool

A web mapping tool was developed to support the dissemination of the results of the PAM modelling to the various stakeholder groups, identifying in each case provisional P acceptance maps across England and Wales. The technical aspects of the tool were developed using the ArcGIS Online suite from ESRI (UK). ArcGIS Online permits data and software functionality to be combined in a cloud-based environment, able to take receipt of data from desktop GIS processing activities ready for dissemination. Table 7 highlights the nominal stakeholder groupings developed guiding the modelling and relative weightings of constraints. The mapping tool presents these scenarios clearly to the user, permitting selection and inter-comparisons to be undertaken. Being 'cloud-based' (Fig. 10), the tool also has the additional advantage that users do not need to have installed and configured Geographical Information System (GIS) installations on their computers, but can instead connect to the data service via the Internet using only their browser. The cloud approach also supports different levels of authenticated access to the tool.

Table 9
National estimates of land-bank in sq. km.

	Group 1	Group 2	Group 3	Group 4	Group 5+
Lower limit	*	7719	7180	7068	7188
Upper limit	*	10,063	14,937	14,744	14,206

Note: For stakeholder Group 1, there are 2293 tonnes excess supply of P_2O_5; For Group 5, biosolids must be moved between NUTS regions.

* Indicates no estimates of landbank since it is worst case where all constraints are considered.

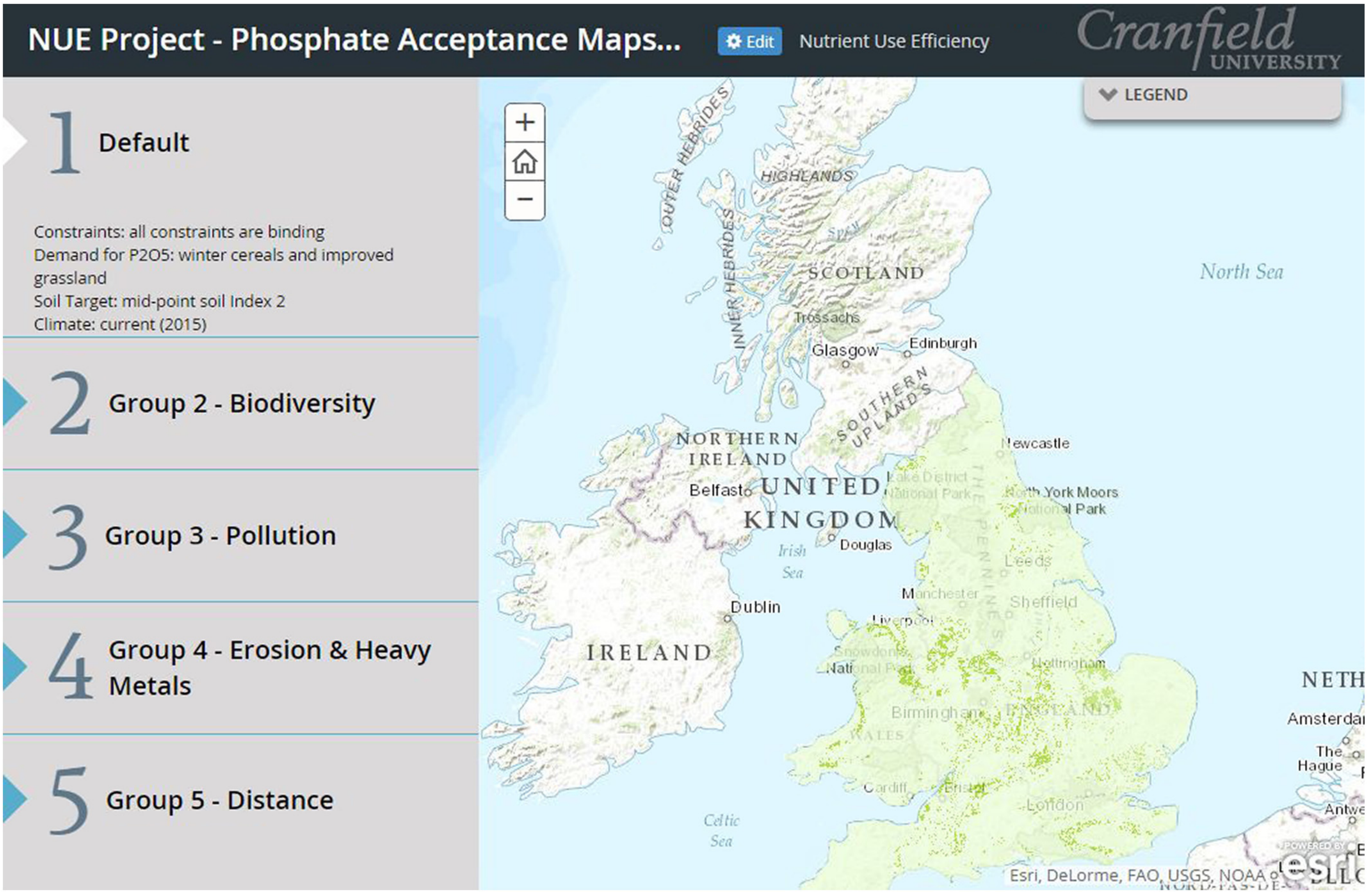
4. Discussion

The novelty of this work is the multi-pronged approach using a weighted approach in geostatistical analysis rather than kriging coupled with stakeholder analysis in order to identify a tool that can be used to inform suitability of landbank to receive biosolids under current and future climatic conditions. A tool of the kind discussed will be valuable to strike a balance when a landbank reaches its capacity to

Table 8
Percentage of the demand for P_2O_5 for winter cereals and improved grass that can be met from biosolids.

NUT 1	Human population ('000)	Tons P_2O_5 equivalent	Stakeholder Group				
			1	2	3	4	5
North-East	2596	2604	**759.6**	168.5	16.8	11.9	24.2
North-West	7056	7077	**140.1**	108.0	26.1	27.2	33.1
Yorkshire+ Humber	5288	5303	**202.3**	114.8	21.8	23.9	31.2
East-Midlands	4537	4550	54.3	42.0	18.0	16.7	18.2
West-Midlands	5609	5625	59.9	40.9	16.1	16.1	21.2
East-Anglia	5862	5879	**126.2**	**103.6**	35.5	34.3	41.6
London	8204	8228	22,329.0	11,04.8	583.3	623.1	6745.3
South-East	8653	8678	97.0	58.9	22.7	32.7	25.2
South-West	5301	5316	67.0	43.7	9.1	11.9	12.2
Wales	3064	3073	44.5	14.3	7.8	7.5	21.0

Note: percentages in **bold** are where biosolids fertiliser exceeds the stakeholder constrained demand. Estimates given the current climate, listed by Local Government Regions (NUTS1).



1 Default

Constraints: all constraints are binding
Demand for P2O5: winter cereals and improved grassland
Soil Target: mid-point soil Index 2
Climate: current (2015)

2 Group 2 - Biodiversity

3 Group 3 - Pollution

4 Group 4 - Erosion & Heavy Metals

5 Group 5 - Distance

Fig. 10. The PAM dissemination tool.

absorb P and identifies new ones to enable new applications of biosolids. The approach adopted in this work can be adapted to suit other geographical locations but as a minimum the dataset has to contain information on soil phosphorus, pH, organic matter, climate and geology. PAM will be hosted on the LandIS website (LandIS, 2017) as a graphical user interface to enable end-users to key in the key parameters and generate maps to identify suitable landbanks. When comparing current and future climatic conditions the corresponding maps that are generated do not differ too much as variations in soil phosphorus are not too drastic due to its slower rate of change. In addition to that the key dataset for developing PAM in terms of soil P comes only from two of our research trials and this can be improved by using more dataset from a wider supply of sources spread across various parts of England and Wales.

4.1. Limitations of the approach

The P acceptance maps presented are subject to several constraints, which should be accommodated in their interpretation. Firstly, there is an assumption that landowners and farmers are economically rational and currently follow, and will continue to follow the Codes of Good Agricultural Practice and the fertiliser recommendations encapsulated in RB209. Associated with this, there is a further assumption that all other major stakeholders are economically rational. This is important as the research has revealed instances where the perception of risk (whether real or imagined) has resulted in technically sound options being rejected. An example might be the stance of the organic farming movement for an outright ban on the use of biosolids. We see no way to predict when or if public concern over, say, a new generation of 'chemicals of emerging concern' such as plastic nano-particles from sunscreens, may result in changes in policy, regulation or use.

A view is adopted in this research that P is the most critical nutrient in biosolids, and that consequently the use of biosolids primarily as a source of N is wasteful and potentially harmful, leading to soils with excessive (from an environmental point of view) concentrations of P. Erosion of P and subsequent eutrophication will thus only occur from soils having an excessive level of P.

Although there is a vast amount of data on the effectiveness of biosolids in commercial agriculture (tens of thousands or farmers have been using it for many decades), empirical data pertaining to these applications is currently inaccessible and is likely to remain so. The available data on nutrient use efficiency is mostly available from the few small-scale, short-term experiments reported in the literature, and most of these experiments were designed primarily with N use in mind. Comparing the results from the few existing experiments is complicated by the observation that the weather has a large effect on yield, and that management efficiency (especially on experimental farms) is known to have a large effect but is never quantified. The research also only considers biosolids produced by the water industry, which is highly regulated.

Estimates of the concentration of P in soils are based on median regression and are subject to relatively wide range of uncertainty (the median regression approach was selected to ensure that the probability of any concentration can be estimated, as well as the "most likely" estimate). The actual measured concentration in a field will depend on local factors and past management practices which cannot be estimated from national data sets. The use of the median regression modelling approach adopted has allowed finer spatial discrimination of the distribution of soil chemistry than is generally possible with traditional geo-statistical techniques (such as kriging), which are forced to assume the phenomena (concentration) follows a smoothly varying pattern irrespective of underlying changes in elevation, geology, land use or soil

Table 10
Stakeholder commentary and reflections.

Issues raised	Reflection
Additional data	
UKWIR have released trials data on fertiliser	A search of UKWIR (https://www.ukwir.org) suggests the most likely report is: “Biosolids: Soil Quality and Fertility Benefits (15/SL/01/8)” Abstract “… This study investigated the effects of twenty years of repeated biosolids applications at four experimental sites.…measurement of serial crop yields and quality were also made. The report provides scientifically robust experimental evidence on the benefits of long-term biosolids applications to soil quality and fertility and to the nutrient supply to crops.”
ADAS review of RB209	It is anticipated that a revision of RB209 will be released soon.
Use of soil chemistry and biosolids data held by all water companies?	This research only reflected data available from United Utilities plc. Other utilities, such as Anglian Water plc are developing their practices such that the next version of their database could permit non-standard requests for data to be met.
Use of UK WIR seminars and technical papers?	This information is not generally made available.
Is the |Nutrient Management Matrix, the same as the Safe Sludge Matrix.	The term SSM can be used as a “short-hand”.
How does PAM approach compare to that in ALOWANCE?	PAM offers a much finer spatial scale, and has a focus on P rather than on N. Additional environmental data is utilised, however, there is less reliance on the June Agricultural Census. ALOWANCE is seemingly no longer maintained. The “professional” version of ALOWANCE is in wide used by consultants, however a full comparison has not been possible due to restrictions in access to this tool.
Data technicalities	
Who owns the data in PAM? Is it confidential? Can it be exported/imported?	PAM outputs are processed by the modelling tool. The underlying data cannot be re-created from these outputs and thus users can freely disseminate the outputs. The underlying data is subject to modern restrictions on knowledge.
Is the spatial scale useful?	Scale in PAM reflects the scale of the underlying data utilised on soils, geology and land cover. In effect, it has a nominal scale of c.1:250,000, although calculations are undertaken at a scale of 1 ha.
What is lost with anonymised soil data?	Environmental trends can still be detected at scales where the location of the landowner is lost.
What are the rates of application?	The PAM model assumes meeting crop needs for P and that farmers follow the Code of Good Agricultural Practice and RB209 – the actual rates of application are often greater than those recommendations, so predictions can be pessimistic (by assuming steady-state, sustainability).
What is the source of biosolids?	The assumption is made that all locations having > 100,000 people are producing biosolids. The actual locations and haul route distances would be useful, but these are not readily available. A future approach could go systematically through the EA records, identifying licenses (noting the need to specify a location every 5 to 10 miles). However, a license gives an upper limit rather than an actual or average level.
Does PAM utilise data held by the Renewable Energy Association, AB, WRAP etc.?	These data have not been forthcoming to date.
How will the PAMs be made available?	Through the web site: http://www.landis.org.uk/services/pam.cfm (LandIS, 2017).
Further research areas	
How will leaching be accommodated in the modelling?	There is found to be limited published data on this, to accommodate this fully would require specific experiments to be undertaken. There is some evidence that biosolids do reduce leaching, but only at the lysimeter scale.
Are other sources of P considered?	Ideally the modelling would incorporate data from digestates (from biogas), poultry and other high P materials. However, in this immediate modelling, only biosolids were considered.
How was Nutrient Use Efficiency (NUE) considered?	There is limited published data on Phosphorous. Predicted NUE lies somewhere between < 10% and > 90%, depending on study conditions.
Considering the movement of nutrients, how are animal feed & bedding accommodated?	PAM modelling assumes all straw is removed.
How is soil organic matter depletion managed?	Addressing this matter in full would require a dedicated survey to consider non-till and reduced till practices (i.e. beyond experimental farms). The literature suggests changes in SOM are always asymptotic.
Are maize and other energy crops factored in?	High nutrient demand crops do produce nutrient rich by-products. However, no national data was available.
Are other forms of digestates considered (liquors, fibres, blended etc.)?	No national data is available – indeed very little specific data in general is available on this topic.
What about the financial benefits accruing to farmers? Prices are subject to fluctuation; wheat prices are very price sensitive (noting some biosolids customers of Anglian Water plc could defer payments by 12 months).	The costs of spreading and incorporating biosolids represent an important component in cost-benefit analysis, however, specific data is lacking. Costs can vary, dependent on the moisture content of the material. Likewise, yield benefits are subject to the weather. One predicted effect of climate change is an increased average yield, but with an increased risk of crop failure! Water companies are not all consistent when it comes to developing their ability to charge.
Legislation/regulations	
Are Assurance schemes accommodated?	The water utility industry is both tightly monitored and documented. Other sectors, e.g. biodigestors, would require specific project.
Public perception is seen as more important than science.	This is a key observation.
This could not easily be used as a screening, or planning tool.	That is agreed, the PAM outputs at present can be seen as a research tool reflecting differing agro-environmental contexts, and scenarios representing the spread of perceived stakeholder concerns.

(*continued on next page*)

Table 10 (*continued*)

Issues raised	Reflection
Land bank/competition	
EA are already observing competition. The response by Water Companies is more mixed.	A future development could permit change in the presentation approach adopted so that a more tabular presentation represents how much of the need for Phosphate fertiliser can be met by biosolids.
What of other types of organic matter?	Currently, little data exists, and the products and producers are diversifying rapidly. A holistic approach to nutrients would be useful. However, this would form the basis for a future developmental stage of research.
What of other economic factors?	Actual biosolids haulage costs are “opaque”. Conversely, the approximate costs are generally consistent.
Land bank issues are becoming worse.	This view expressed by stakeholders is in qualitative agreement with the modelled predictions of PAM.

type and stratified kriging (with multiple strata) is impractical in this case.

The research methods presented are reliant on existing data that is not always widely accessible. Data collected by trade associations and voluntary regulators is subject to some form of “cost recovery”. Despite assurance to maintain anonymity, “commercial in confidence”, “intellectual property rights” and other constraints, certain data required cannot always be obtained easily. The methods sought to reflect the choice of scenario stakeholder groupings, where the concerns of stakeholders were characterised across five nominal representative viewpoints. Although these were derived after consultation with stakeholders, stakeholders will generally have a more nuanced perspective. The characterisations adopted express only those concerns that can be encapsulated in the national data sets available. The effect of local environmental conditions and especially of ‘NIMBYism’ cannot easily be modelled. Equally, the characterisation of stakeholder concerns using nationally available data to identify areas where different perspectives agree and where (spatially) there is likely to be disagreement is considered a useful outcome. Aspects related to PAM usage under future climatic conditions has some uncertainties related to the climatic input data which needs to be considered when interpreting any model outputs.

The research reported has several innovative aspects. In the first instance, it has resulted in the production of the first national Phosphate Acceptance Maps, identifying where P is required by two important crops, winter wheat and improved grassland. These crops were selected as being those currently receiving a high proportion of biosolids, and being those likely to continue to do so in the future. Application of biosolids is permitted on many other crops, but with increasing constraints. The research has also provided for the first time the means to assess, even approximately, how much of the demand for P fertiliser could be met from biosolids.

The PAM tool can be used to target application of biosolids to match crop demand. Currently biosolids are only applied if soil heavy metal limits are not breached according to regulatory guidelines. Whilst this is sensible, any build-up of P in soil is less monitored and the requirement of the crops is then not fully considered. With the availability of PAM, landowners can monitor the build-up of P, and adjust biosolids application accordingly in tandem with crop requirements.

According to the Agricultural Industries Federation (AIC, 2013) 21% of arable land and 32% of grassland is deficient in Phosphate. However, in 2014, a greater proportion of land still receives fertiliser; 49% of arable land and 41% of grassland is fertilised with an average of 59 and 24 kg P_2O_5/ha respectively (Defra, 2015). There is a long-term declining trend in P_2O_5 fertiliser use, and this is reflected in a small decline in agricultural soils detected by the RSSS (Representative Soil Sampling Scheme) in four surveys conducted between 1971 & 2001 on ~700 farms (Baxter et al., 2006).

4.2. Reflection of stakeholder views

Stakeholders who participated in the workshops raised a series of questions about the project outputs, summarised in Table 10.

5. Conclusion

The study has demonstrated the potential of the newly developed PAM tools to provide decision support for UK water utilities and the land-based industries, and the assessment of suitability of land to receive biosolids. The research method has involved the development and application of a modelling approach for phosphate acceptance, drawing from a collation of the core geographical and descriptive data themes required. These data describe both the environmental characteristics of the land under assessment, as well as the expression of nominal stakeholder values and protected areas. There were engagements with four nominal stakeholder groups which together have supported the development of a useful, holistic tool for end users such as water utilities, agronomist and farmers. The representation of stakeholder groups highlights how the available land bank could be reduced to an insignificant area, emphasising the need for continued dialogue and the need to resist impulsive reactions to risk.

These areas of concern highlight the requirement for a rational scientific, evidence-based decision support methods for assessing suitability for biosolids application. The PAM model provides a sound basis for addressing this need, layering over the model the means to capture a range of realistic scenarios, developed with industry practitioners, to allow exploration of the consequences of different land management strategies. The PAM approach integrates a wide range of geospatial and semantic data inputs to permit the modelling to be undertaken. In the UK, these data are available (some freely, some commercially), and can be accessed to build national and regional approaches. The issues addressed in the PAM modelling span borders and thus, where the data required is forthcoming, the methods demonstrated do also have the potential to support wider application in other national contexts.

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