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Developments in land information systems: examples demonstrating land resource management capabilities and options

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Abstract

Land Information Systems (LIS) provide a foundation for supporting decision-making across a broad spectrum of natural resource applications: agronomic, environmental, engineering and public good. Typically, LIS constitute a computerized database repository holding geospatial components, 'mapping unit' geometry and related georeferenced materials such as satellite imagery, meteorological observations and predictions and scanned legacy mapping. Coupled with the geospatial data are associated property, semantic and metadata, representing a range of thematic properties and characteristics of the land and environment. This paper provides examples of recent developments of national and regional LIS, presenting applications for land resource capabilities and management. These focus on the 'Land Information System' (LandIS) for England and Wales, and the 'World Soil Survey Archive and Catalogue' (WOSSAC) and consider Agricultural Land Classification in Wales, an Irish land and soil information system, and a scheme to optimize land suitability for application of palm oil biofertilizers in Malaysia. Land Information Systems support purposeful environmental interpretations, drawing on soil and related thematic data, offering insight into land properties, capabilities and characteristics. The examples highlight the practical transferability and extensibility of technical and methodological approaches across geographical contexts. This assessment identifies the value of legacy-based natural resource inventories that can be interoperated with other contemporary sources of information, such as satellite imagery.

Keywords: Soil inventories, land capability, agricultural land classification, palm oil biofertilizers, legacy data reconciliation

Introduction

Land Information Systems (LIS) provide a technical foundation for supporting decision-making across a broad spectrum of natural resource applications: agronomic, environmental, engineering and public good. The LIS provides a 'framework to combine land surface models, relevant data and computing tools and resources' (Kumar *et al*., 2006). Typically, LIS constitute a computerized database repository for holding geospatial components, comprising 'mapping unit' geometry, and related georeferenced materials such as satellite imagery, meteorological observations and predictions and scanned legacy mapping. Associated property, semantic and metadata, representing a range of thematic properties and characteristics of the land, and related subjects are also held. Geographical Information Systems (GIS) provide a natural technological basis for the development of LIS, being able to combine disparate sources and types of geospatial data, and providing the basis for integration of other types of information, such as remote sensing imagery. GIS further adds geoprocessing capabilities that can be undertaken on its data; however, it cannot alone provide the full range and scale of data management functionality required of LIS. Thus, an additional database management system can be employed to hold, manipulate and serve data as required, depending on scale and application.

This paper aims to demonstrate some recent developments in the field of LIS, both in the UK and internationally, presenting three examples of their application in assessing land resource capability and management. The paper draws upon the 'Land Information System' (LandIS), set up in 1987, whose data extend across England and Wales, and the

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applications it supports (Keay *et al*., 2009; Hallett *et al*., 1996). LandIS incorporates the National Soil Map; the Soilscapes map; the National Soil Inventory of soil properties; >300 county, regional and national soil publications, including maps; some 250 000 auger bore records; 8 000 soil profile descriptions; 15 000 field records; nearly 800 farm and localized land classification maps; a national upland erosion survey; lowland peat survey; clay mineralogy; X-Ray diffraction studies; >10 000 photographs, predominantly of soil profiles and their associated landscapes, from the UK and overseas, as well as examples of particular soil issues, threats and functions (see www.soilsworldwide.net and www.landis.org.uk/services/soilsguide); aerial photographs; satellite images; and many hundreds of soil thin sections, mounted on glass slides. Thin sections are available for all described soil series, based on each horizon of representative profiles. Digital scans of many of these slides are included within the photographic collection. Developed in parallel with LandIS is the 'World Soil Survey Archive and Catalogue', or WOSSAC, established in 2002 (Hallett *et al*., 2011, 2006). The WOSSAC catalogue includes some 27 025 international soil-related items (including maps, official surveys, consultant's reports and related grey literature, monographs, books, academic papers, research theses, satellite and aerial imagery, many photographs of sites and profiles, and numerous rare and seminal publications). Many items in WOSSAC are unique and fragile, being derived from 352 territories worldwide, representing many lower- and middle-income countries (LMICs) which would now be impossible to locate in-country.

Applications of land information systems

Land Information Systems provide a foundation for a broad range of thematic environmental applications, within a given geographical context (localized, national or regional in scope) (Figure 1). The core data typically describe the inherent, immediate properties and characteristics of the land, which can be combined with other resources, such as satellite imagery, cadastral information and climate observations and projections. LIS draw upon a range of modelling and geoprocessing technical capabilities to combine these resources to assess land suitability, such as for agriculture (Hallett *et al*., 2003). A temporal context can be introduced by including indicators of environmental change associated with a static survey and inventory, or with ongoing monitoring, such as soil degradation threats (Gregory *et al*., 2015). Likewise, modelling applications can explore the likely consequence of fate and behaviour of compounds in the soil, or the consequence for soil functions of changing climate patterns or land use. The outcomes from LIS permit key actors to make both informed decisions and effective plans, as well as support environmental education and awareness (Hallett & Caird, 2017).

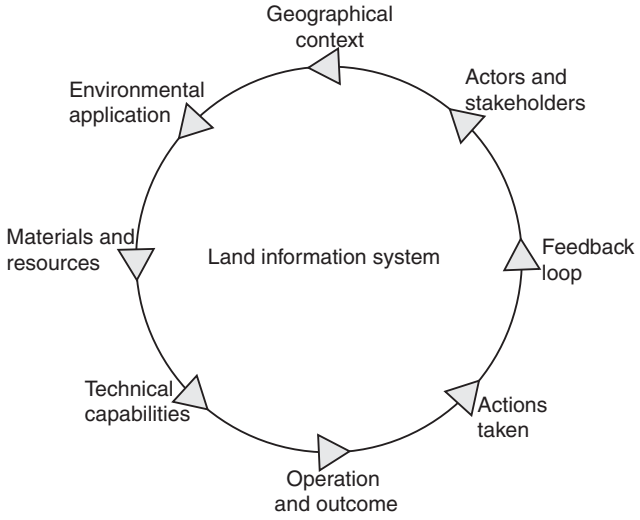


Figure 1 The Land Information System (LIS) Lifecycle.

Examples of land information system application

Examples of LIS applications and approaches are selected to demonstrate their range and extent and highlight their application to environmental issues. The first outlines the establishment of a new Welsh Agricultural Land Classification (ALC), for use at a policy level to help plan and administer appropriate national agricultural support mechanisms. The system is extensible and can be transferred successfully to other national contexts. The second example outlines the production of a new national soil map and a national soil and LIS for the Republic of Ireland. This uses a unique method, which fuses harmonized legacy data and soil associations predicted by digital soil mapping, to produce a new national-scale soil class map. The final example articulates the use of the materials in WOSSAC, together with other sources of contemporary data, such as high-resolution satellite data, to identify a suitable land bank in Malaysia for the application of biofertilizers derived from palm oil.

LandIS and predictive agricultural land classification in Wales. In England and Wales, LandIS has been applied to a broad range of thematic applications over its 30-yr existence (Table 1). There is also a public education and awareness role, whereby information is provided in the form of general soil descriptions for given sites. Thus, LandIS is accessible through services including the Soilscapes Viewer and the Soil Site Reporter (www.landis.org.uk).

The broad range of applications for which LandIS has been utilized far surpasses the scope and purpose for which the soils data it contains were originally recorded. The Soil Survey of England and Wales (SSEW) was founded in 1939 (Hollis & Avery, 1997). In the post-war years, considerable attention was given to planning food security. However, as

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Table 1 Application themes developed for the LandIS Land Information System

Theme	Examples	Selected references
Developing good environmental practice – pollution control	CatchIS (Catchment information system) pesticide fate and behaviour Sludge and waste to land	(Brown *et al*., 2002)
Geotechnical applications	Corrosion risk Shrink swell capacity Suitability for soakaways	(Pritchard *et al*., 2014)
Water resources Quality & management	Hydrology of soil types Groundwater vulnerability	(Boorman *et al*., 1995)
Future planning strategies	Climate change impacts Soil carbon dynamics Land use change	(Keay *et al*., 2012; Gregory *et al*., 2015)
Land suitability and resources assessment	Crop suitability Tree suitability Ecological habitat creation Peat data	(Burton & Hodgson, 1987)
Land management	Soil structure Machinery work days Land drainage	(Palmer & Smith, 2013)

Source: after, LandIS (2017).

the decades passed, more focus was directed towards additional environmental and engineering applications, as well as impact assessments of activities affecting the soil resource. In more recent years, with the growing realization of consequences of the expanding population, there is once again a strong focus upon food security and sustainable intensification, completing an arc of development, underlining the extended usage of the data held within.

The ALC system used in England and Wales was developed for land use planning, to help steer urban development away from areas of land with the greatest flexibility for agricultural use. The limiting physical factors are identified as follows: climate (rainfall, transpiration, temperature and exposure), and soil (depth, texture, structure, stoniness and available water capacity), and factors influenced by both climate and soil (wetness, droughtiness and flood risk) (Keay *et al*., 2012). These factors are used to classify the land into five grades; Grade 1 being excellent quality and Grade 5 being of very poor quality, with Grade 3 further subdivided into Grades 3a and 3b. The Best and Most Versatile (BMV) land for agriculture is considered as ALC Grades 1, 2 and 3a.

The combination of soil mapping, characterizing the soil factors in an area, together with climate data from the Meteorological Office, allows production of countrywide ALC maps at various scales. Previously, the only national level map was the Provisional ALC map, created in 1974 at 1:63 360 scale. This was created before a decision was made to split Grade 3 in two, and the map was therefore not appropriate for defining BMV land.

Methods: A new ALC map has been developed for Wales on behalf of the Welsh Government using the National Soil Map of England and Wales (Cranfield University, 2001). In England and Wales, soil profile characteristics are used to define soils at four levels in a hierarchical system; general characteristics are used at the highest level to provide broad separations, and more specific ones at lower levels permit increasingly precise subdivisions. The four categories are, in descending order, major group, group, subgroup and series. (Avery, 1980; Clayden & Hollis, 1984). The National Soil Map of England and Wales identifies geographical 'soil associations' identified by the most frequently occurring soil series and by combinations of ancillary soil series.

In 1988, the climatological data for Agricultural Land Classification were published at a 5 km resolution, with instructions for interpolating the climate data from the four nearest surrounding 5 km points to a site and adjusting for altitude differences (Met. Office, 1989). Using this approach, and drawing on the Ordnance Survey Terrain 50 data to provide elevation, it was possible to generate the required climate data on a 50 m raster. The modelling process integrated geospatial data layers representing soil, climate and terrain factors, each having differing resolutions. The model worked from the finest resolution, the 50 m altitude-derived raster points, and for each of these, by an intersection process, the soil and climate properties were spatially joined. For each 50 m grid, the soil association covering the maximum geographical area was selected to represent the soils.

Owing to the limitations of its cartographical scale (1:250 000), the National Soil Map identifies soil associations, being those groups of soil series (or soil types) that commonly occur together, rather than specific individual soil series. Soil associations were originally adopted to represent the whole land area of England and Wales, with standardization of the member soil series for each. Inevitably, this process 'smoothed' out certain locally occurring soils for given associations, such that when the national map was produced, these associations were rationalized and only the most common series retained, with average proportions of each given. For contemporary modelling purposes, however, this standardization was considered to remove valuable localized knowledge, where

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regional variation within the composition was not identified at the national level. To tailor the national soil map for Wales, an assessment was made using a set of national auger bores, as well as all available detailed soil mapping to improve and extend the composition of soil series in the mapped soil associations. This assessment was conducted by four of the original soil surveyors from the Welsh National Soil mapping programme. At the conclusion of this process, although the mapping linework remained constant, the soil series belonging to each of the Welsh associations had been reconsidered and there was thus a greater representation of the diversity of Welsh soil conditions. It was this revised data that was used for the subsequent ALC modelling. In summary, there is now a new 'Welsh soil association map' which can be used in future research, whilst the original soil association map will still permit harmonized use across both Wales and England.

Drawing on the new Welsh soil association map, the collected soil series across all the associations were assessed against the seven ALC criteria, namely Climate, Wetness, Drought, Gradient, Soil Depth, Stoniness and Texture. Subsequently, a spatial modelling approach was used to iterate through each of the smallest components from the soil, climate and terrain intersection noted above, being a 50 m grid. For each of these grids, the soil association was extracted, and thus each of its member soil series, together with their ALC criteria. For each of the seven criteria, the grade covering the largest geographical area was used to classify the grid, and the overall ALC grade was taken as the most limiting of the criteria.

Results: The new predictive ALC map for Wales was produced at 1:250 000 scale, expressed as a 50 m raster data set (Keay *et al*., 2016) (Figure 2). A further stage of analysis assessed how climate change might affect the classification results (Figure 3). A related 2012 study assessed the impact of climate change on ALC using the National Soil Inventory sites on a 5 km grid for the soil properties and the UKCP09 climate scenario data (Keay *et al*., 2014); climate, wetness and drought criteria are all influenced by changing climate parameters. Although the increased temperature and rainfall improved the classification for the climate and wetness criteria, the method for assessing droughtiness was shown to be highly affected by the changes and the future climate parameters for drought led to much of the land being assessed as ALC Grade 4. Using the same approach to interpret future climate scenario data onto a 50 m grid based on altitude, as used for the Welsh predictive map, it is possible to assess how land classes may vary; for example, adopting the high emission scenario would lead to the majority of BMV land being lost by 2080.

Discussion: The assessment of drought for ALC is based on models for unirrigated wheat and potato crops. There are opportunities to mitigate these assessments using crop selection, breeding and irrigation. ALC is a relative scale, and the current BMV land will remain the same class in the future, although the land's versatility will change over the years to favour crops that flourish in warmer, drier summer conditions.

The new assessment allows the Welsh Government to consider the ALC of land in Wales and to interrogate the data, revealing the contributory factors leading to particular grade assignments. The output map of ALC grades will become available for public access and reference. A long-term aspiration is to develop a dual-use product, predicting ALC grades for planning purposes, as well as serving as an interactive model (assigning different climate, crop, flood and drought parameters) to inform Welsh Government policy decisions across their agricultural and land use portfolios.

The production of a new national soil map and national soil and land information system for the Republic of Ireland. A gap analysis (Daly & Fealy, 2007) revealed how the lack of suitable national-scale soil information in Ireland was hindering the development of national environmental policies and reporting requirements under European Directives (e.g. the Water Framework Directive). A new national soil map and associated data were required to support these strategic national developments and also to be compatible with existing soil survey coverage in other member states of the European Union (1:250 000 scale). The development of a new map and soil data used existing thematic and property data to produce predictions of soil data in areas having little information. The resultant harmonized national soil map provides a basis for policy and strategic decisions. The soil data were organized, following the LandIS structure, to provide a comprehensive information system holding thematic and attribute content. Approximately 45% of the country was previously mapped at 'county level' under An Foras Talúntais (AFT). In the remaining areas, soil units were mapped using digital soil mapping methods and validated with field observations. The associated information system was designed to support open web access to data (Figure 4)

Methods: An initial phase of legacy data harmonization was undertaken to rationalize the different soil classifications used in the original soil surveys, producing a single, harmonized list of national soil series and mapped soil associations. This created a standard training data set that could be used as input to the modelling phases, also ensuring compatibility between the different legacy data sets (county soil maps), which were transferred to the final map. Soil profile descriptions and analytical data were also captured from hardcopy into a standardized electronic database form to feed into the information system.

The legacy data (training areas) were split into broad soil landscapes ('soilscapes') using expert knowledge, with the

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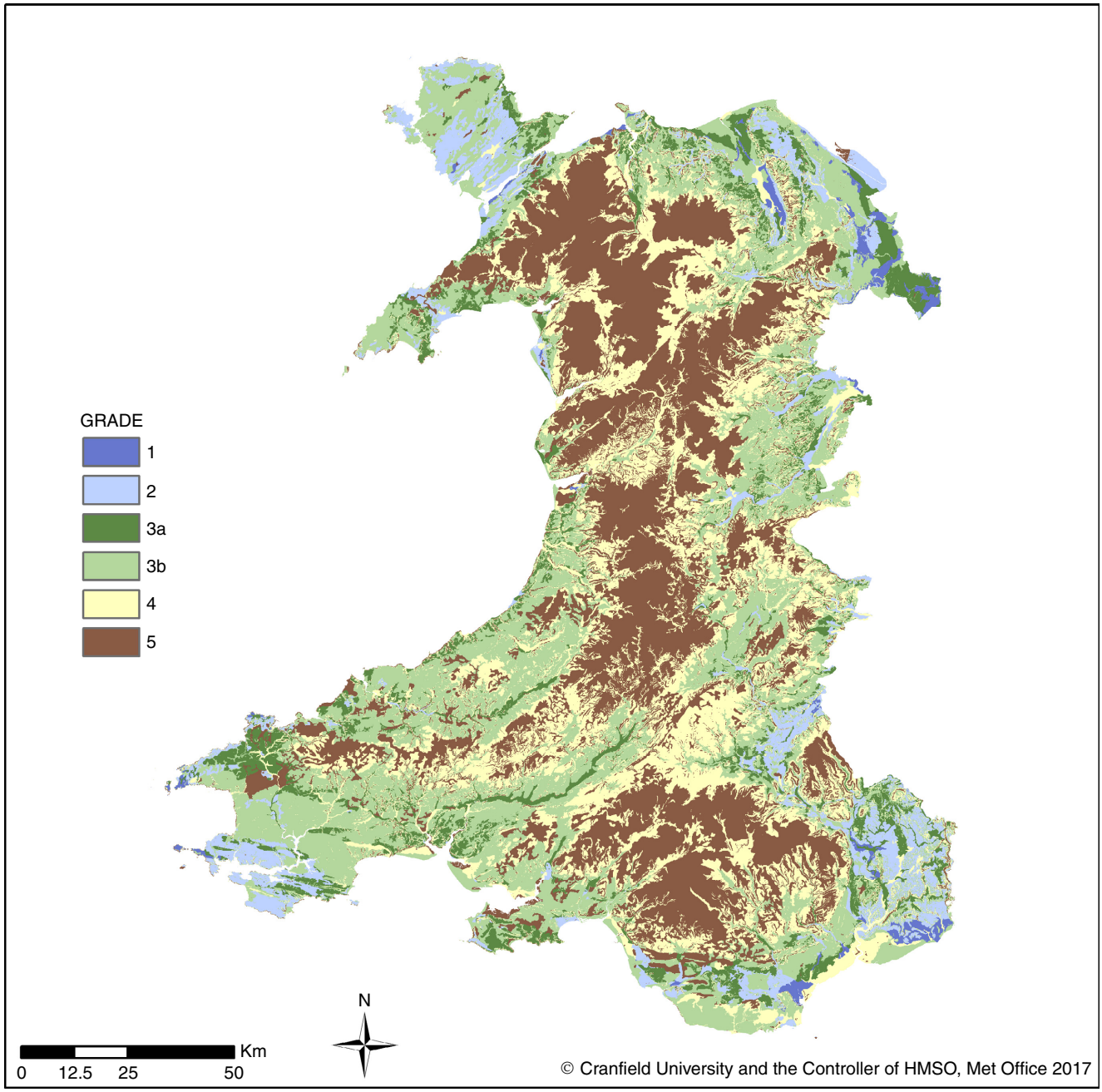


Figure 2 New predictive ALC grades for Wales.

rationale that this would optimize the models used to predict soil associations within these areas. As the soilscapes were not available for the unmapped counties, they were extrapolated using two approaches. The first approach was feature space analysis, an index used to describe the similarity of five broad environmental variables (general soil map, geology, elevation, slope and subsoil) in the training areas, compared to the extrapolated areas. Thus, for the general soil map, the index compared the frequency of the different soil types between the training area and the unmapped area to identify similarities, which could be used to assign a particular soilscape. The second approach used a decision tree classifier approach (Random Forests) that modelled the relationship between the environmental variables and the soilscapes (Mayr *et al.*, 2014a). Within each broad soilscape, statistical models were developed to predict relationships between numerous spatial data sets (environmental covariates) representative of soil forming factors (SCORPAN) and the soil associations in the landscape. These models were deployed in the unmapped

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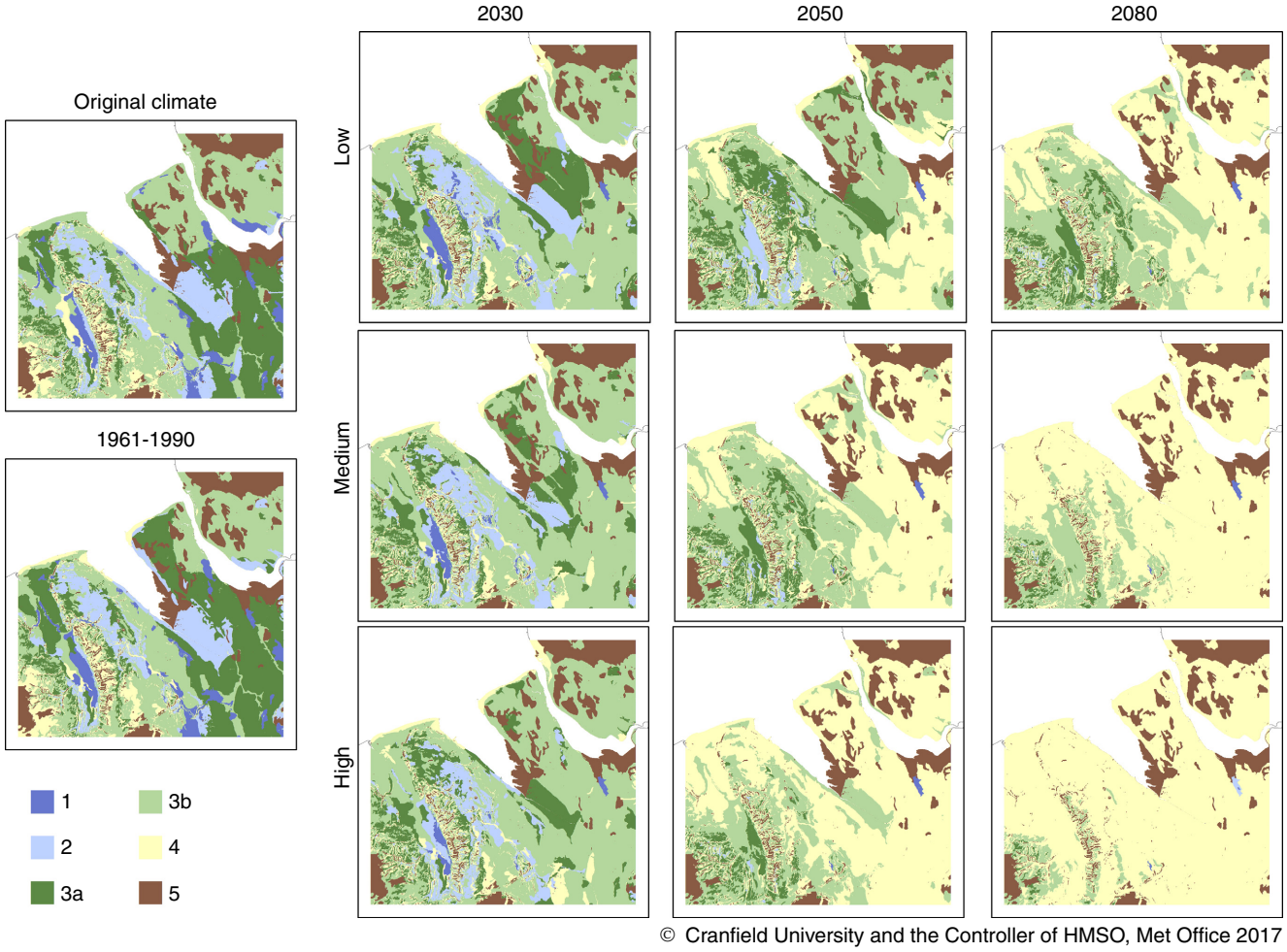


Figure 3 New predictive ALC grade for Wales, showing the effect of climate change on the classification as currently applied. *Note:* The axes relate to the results of modelling ALC using climatological data arising from the UKCP09 projections, for three emission scenarios and three time periods. Empirical climatological assessments are shown to the left.

areas to predict soil distribution from the relationships with the other environmental variables. Two machine-learning algorithms (Bayesian Belief networks and Random Forests) were used to establish inference between these environmental covariates and soil distribution (Mayr *et al.*, 2014b). The predicted soil associations in the previously unmapped areas were then validated against 11 000 field observations by identifying soil series present in the predicted soil associations. The resultant map underwent validation procedures to update the soil mapping units (Simo *et al.*, 2015) based on observations and taxonomic distance of the predicted and observed soil class. As the training data did not always represent the soils in the unmapped area, different combinations of soil-landscape units were identified during the field campaign and thus additional soil data were generated. This included new soil series sampled as soil profile pits at representative locations across the country and the addition of new soil associations on the map. A total of 225 soil pits were described that included original and new soil series. These were sampled and analysed in detail and were used to generate additional soil data to derive an updated national classification system.

Results: The final national map (Figure 4) is a hybrid of the original harmonized county soil maps and the validated modelled soil associations for previously unmapped areas. It includes new soil associations discovered during the field programme. The map identifies 58 soil associations with 213 soil series recognized across the Republic of Ireland. Each soil series has a representative profile with associated field profile descriptions and a summary of key soil analyses by horizon (e.g. particle size, organic matter and CEC). This data are stored electronically in the information system, along with site, landscape and soil profile photographs of the new samples from the field campaign.

Discussion: The unique methodology adopted in this study fuses data collected through traditional methods of soil

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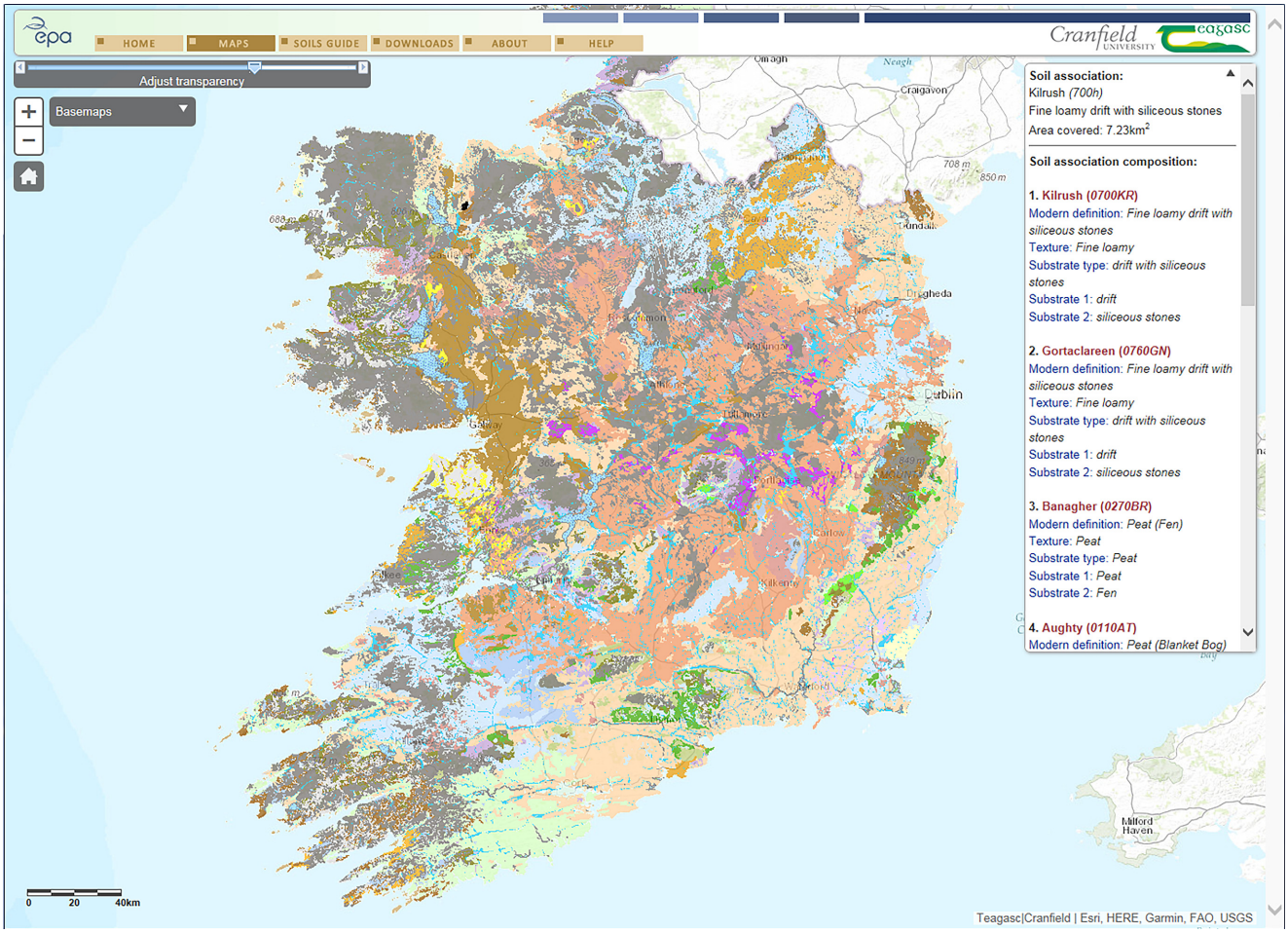


Figure 4 The Irish Soil and Land Information System (soils.teagasc.i.e.), showing the new national soil map of Ireland.

survey with that from predictive mapping. The principle of the information system was similar to LandIS whereby data were stored in and retrieved from the central database through an SQL-enabled relational data structure. The system supports the complete set of soil information, derived from the new field programme and modelling activity, with previous soil survey data. Prior to this, there had been no harmonized computerized system that stored and manipulated soil data for the Republic of Ireland. Crucially, the map and associated data are made publically accessible, online. The soil map can be interrogated, and additional information is accessible through an online soils guide with downloadable datasheets (Creamer *et al*., 2014).

The Irish Soil Information System can now provide updated soil input to river basin management plans through the development of more specific models for pollutant transfer through soil to surface and ground waters (Archbold *et al*., 2016). It can enhance regional and national agri-environment policies and provide practical advice to farmers.

WOSSAC and targeting of land suitability for the application of palm oil-based biofertilizers in Peninsular Malaysia. The theme of the materials held in the World Soil Survey Archive and Catalogue (WOSSAC) is predominantly soils and soil survey (see Introduction), although, by nature of the accessions to the archive, there are also many items on related themes such as land use and cover, natural resources, geology, climate, biophysical, topography, socio-economic and cadastral. The spatial holdings mostly represent the Anglophone countries in Africa, as well as countries in the Middle East and South-East Asia. Figure 5 shows the outline of the geographical 'bounding box' (geographical extent) of each of the items in the WOSSAC archive for which data are available. The figure presents a panoptic view of the geographical extent of the holdings in the archive, showing clearly the relative density of materials in Africa, Europe, the Middle East and South-East Asia. Figure 5 further identifies areas not well represented by the current collection, that is North and South America, Russia and Western Australia.

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Managing the materials in an archive such as WOSSAC requires the accession of materials and their preparation for usage and application. Initial accession involves receiving materials, making any immediate physical repairs (e.g. torn sheets, frayed edges and map hangers), shelving, cataloguing and labelling. Descriptive metadata is recorded for each item catalogued, consistent with the Dublin Core Metadata Initiative standard (DCMI, 2012), which can then be accessed through the online catalogue search tools (www.wossac.com). The next action in preparing these 'legacy' materials for (re) use in LIS necessitates digital scanning of materials, serving also as an insurance against damage or loss. A process of resource inclusion then needs to be undertaken, dependent upon the nature of the artefact (Figure 6). For a given LIS application, relevant legacy materials (e.g. soil maps representing a given study area) are selected from the catalogued collection, captured in digital form and, given co-ordinates aligned to a common mapping reference, permitting geographical juxtaposition of data sets. Once this is achieved, relevant data features can be extracted through digitization and transformed to a consistent and coherent format before their inclusion in LIS. The WOSSAC archive may thus be considered a resource upon which LIS applications can draw. LandIS by contrast represents a fully formed LIS architecture, where comprehensive national, digital soils data mapping and property resources are available.

Malaysia is the second largest producer and exporter of palm oil worldwide (Kala *et al*., 2009; Mohammed *et al*., 2011) and generates considerable biomass residue from plantation and milling activities (Hassan *et al*., 2005; Agamuthu, 2009; Shuit *et al*., 2009; Griffin *et al*., 2014), leading to environmental and ecological concerns to humans (Vakili *et al*., 2014). However, there are some uses for the residue, such as for mulch, which can help recycle some nutrients and protect soil from erosion. The Malaysian Palm Oil Board (MPOB) estimates that the nation's 436 palm oil mills in 2013 had a total annual processing capacity of 105 million tonnes of palm oil and palm fresh fruit bunch. The

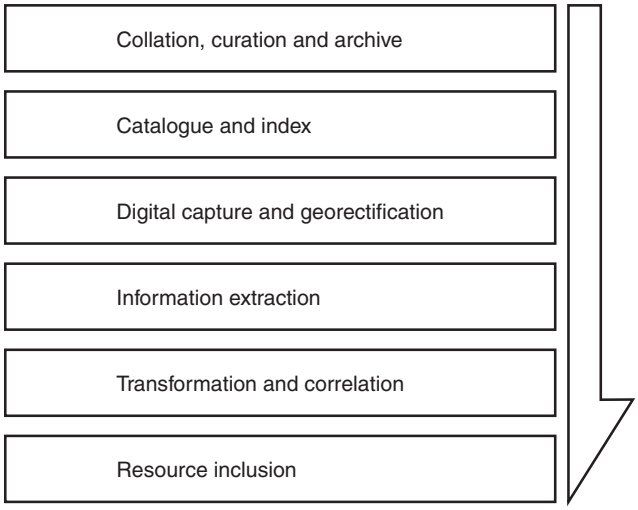


Figure 6 Introducing legacy materials within an LIS application.

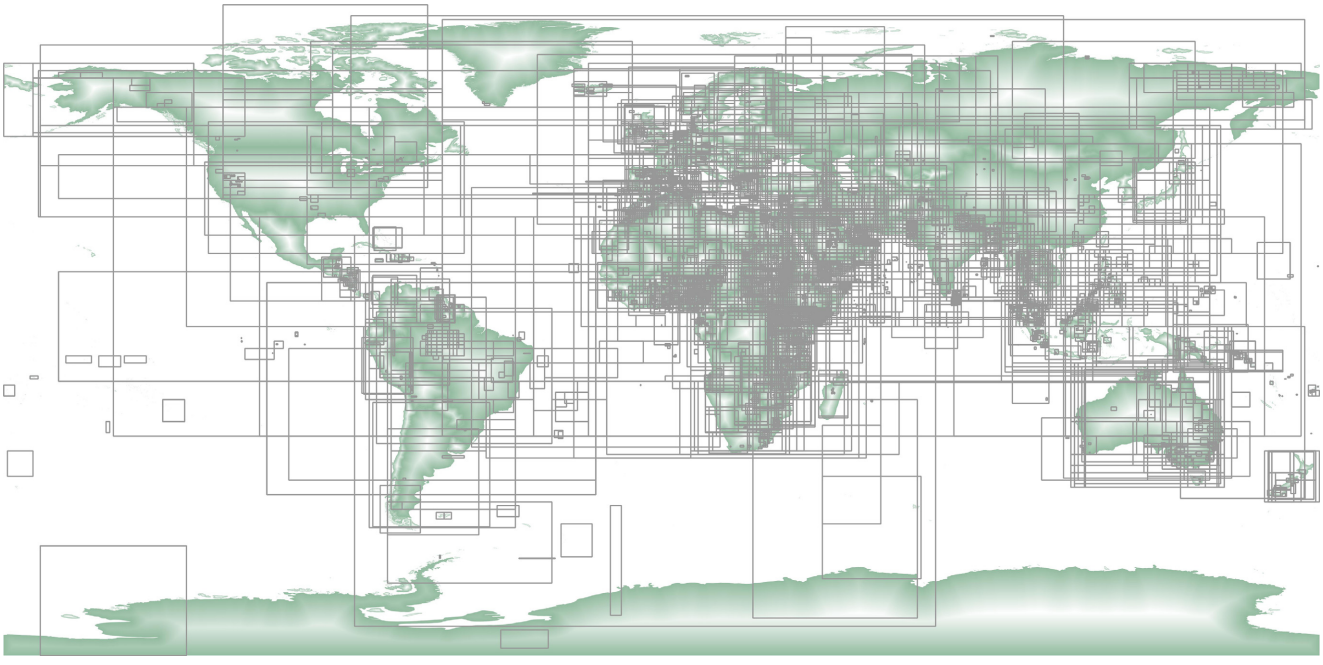


Figure 5 The spatial extent of holdings within the WOSSAC archive. *Note:* The bounding boxes are shown for each geocatalogued map.

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waste generated from the milling processes includes palm kernel shells (PKS), palm pressed fibres (PPF), empty fruit bunches (EFB), palm oil mill effluents (POME) and palm kernel cake (PKC). Other residues, for example palm oil trunks and palm oil fronds, remain in the plantation and, if not properly utilized, may lead to significant environmental concerns.

This example demonstrates the use of WOSSAC, to create LIS specifically to determine suitability of land to receive application of palm oil biofertilizers. The system represents a preliminary model that incorporates the effects of soil variation, riparian protection, transport distances and modes of application on the distribution of biofertilizers in Peninsular Malaysia.

Methods: The model is based on a simple and flexible combination of factors which affect decisions on the distribution systems for palm oil biofertilizers. It allows for considerable variation between estates, according to local conditions and management priorities. There may also be intra-estate variations where local environments are heterogeneous. The model is intended for application at estate level, but could also contribute to regional or national overviews. Model inputs are held as separate GIS layers, depicting soil patterns, local stream network, estate transport network and transportation distances from the composting facility.

The impact of *soils* on biofertilizer distribution is affected by two groups of overlapping soil capacities. The first is the ability of the soil ecosystem to incorporate and process large but episodic inputs of organic materials. The second relates to soil attributes that enable palm oil yields to respond positively and profitably to the increased nutrient supply and improved physical soil conditions resulting from the application of biofertilizers.

At present, there is a lack of detailed and comprehensive data on which particular attributes or combinations in Malaysian soils are important for these particular capabilities. In the current model, soil taxa (soil series) are assigned to biofertilizer acceptance classes according to their general suitabilities for palm oil cultivation. This favours deep, well-drained and fine-textured soils, such as those developed from shales, basalts and some alluvia (ISPM, 1972; Paramanathan, 2015). An alternative future strategy is to prioritize biofertilizer application on soils that will be significantly improved by the addition of large quantities of well-composted organic matter, favouring coarse-textured and weakly structured soils, even though these are generally less productive for palm oil (Paramanathan, 2016; Tie, 2016 – personal communication). The model is flexible with respect to soil ratings, designed such that future iterations can explore the economic and practical implications of the different strategies. It is anticipated that local decisions will largely depend on financial costs and benefits.

As obtaining access to modern cartographical soil mapping in Malaysia can prove a matter of some political sensitivity and legacy surveys were available from the WOSSAC, which holds almost 700 items covering Malaysia, no maps were procured from the Malaysian authorities. However, locational data for the mills were procured from SIRIM (Standards and Industrial Research Institute of Malaysia). Figure 7 shows the distribution of pertinent soil surveys considered in south-eastern Peninsular Malaysia. Overlain points represent locations of palm oil mills. In the final analysis, the central mill location, Kilang Kelapa Sawit (KKS) Sungai Jernih, was selected, located in Jalan Raja Chulan, Pahang Tenggara (103.100°E, 3.339°N) (Figure 7, central site); this site is covered by medium-resolution (1:63 360) soil mapping.

Malaysia's Environmental Quality Acts of 1979 and 2005 impose stringent regulations for the natural environmental protection, including water resources. Release of prescribed materials, such as POME, into surface and groundwater is forbidden. Although not yet legislated, it seems prudent to include the spreading of palm oil biofertilizers as a potentially harmful activity and to exclude them from within at least a stream's width of stream banks (S. Paramanathan & Y-L. Tie, personal communication, 2016). This model precludes distribution within riparian protection zones and accommodates different zone widths, with 50, 25 and 10 m buffers, deemed locally as appropriate. For illustrative purposes, the drainage GIS layer currently delineates the main*stream and drain networks*, with 50 m buffers to either side.

Although the weight and volume of POME and EFB are reduced by composting, biofertilizers remain heavy and bulky. Combined with the requirement that biofertilizers be spread at agronomically beneficial rates and without harm to the standing crop, the reduction in *transportation distance costs* is a major consideration in the planning of their distribution. The costs have two major components: road haulage from the composting facility to field edge, and within-field distribution.

Road costs are best quantified as trucking times. However, data for these are not currently available, and so road distances are taken as a surrogate. Because of the high densities of estate roads, road distances approximate to straight-line distances; this study zones them as concentric zones, radiating 1, 2 and 3 km from the mill. The estate roads were digitized manually from aerial photography and satellite imagery in Google Earth and from Digital Globe (WorldView-3). Not all estate roads are the same quality, and optimum routes and trucking distances may deviate from the apparently shortest route.

In both identifying stream and drainage networks together with transport routes, where possible, features were captured from high-resolution satellite imagery of WorldView-3. This provides a 31 cm panchromatic ground resolution and 1.24 m

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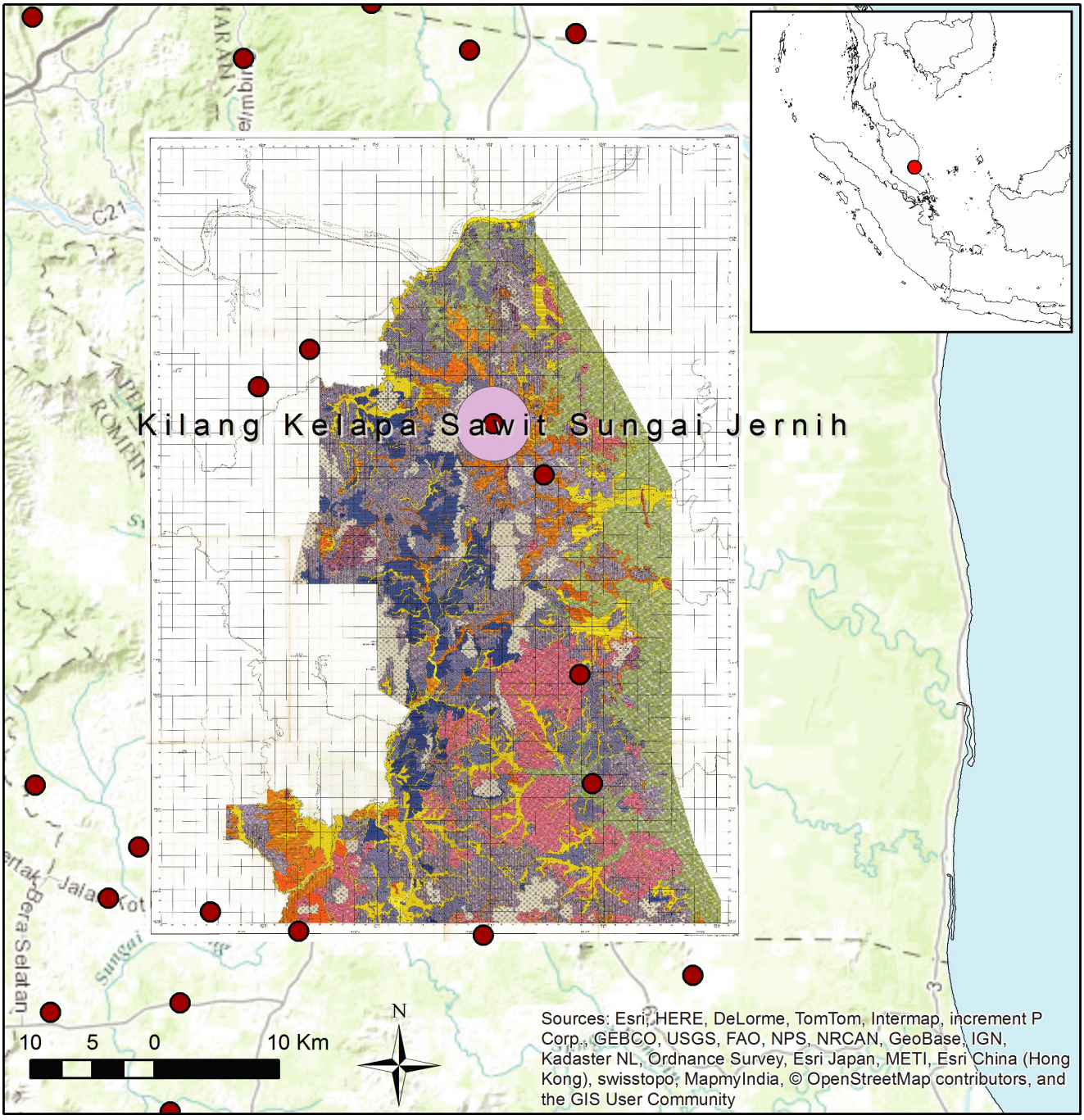


Figure 7 Locations of Kilang Kelapa Sawit (KKS) Sungai Jernih mill. Note: Points indicate local oil palm mills; KKS Sungai Jernih mill location with 3 km radius; Soil map (Foundation of Canada Engineering Corp, 1951).

multispectral ground resolution (www.satimagingcorp.com/satellite-sensors/worldview-3). However, the imagery is partially obscured by clouds in places, and also features are obscured in areas of mature palms where the palm oil crowns meet and cover the ground surface. In these cases, distinction of roads and linear drains proved difficult. A parallel, coarser validation of stream networks in the 3 km zone was derived from a 90 m pixel digital terrain model (DTM) obtained from a hydrologically corrected Space Shuttle Radar Topography Mission (SRTM) data set (SRTM srtm.jrc.ec.europa.eu). Network connectivity tools were further used to validate both stream and transport networks.

Planting patterns on the local soft peaty soils makes transport difficult in some places, necessitating biocompost to

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be spread from the roadside. To achieve this, it is assumed that manual handling is, or will soon become, too expensive, thus mechanized distribution systems are considered, for example blowers or elevators – the choice depending on the handling characteristics of the biofertilizer, topography and available spreading resources. For this study, it is assumed the spreading systems will be able to reach distances of 15 or 25 m from roadside. There are currently two GIS layers for this factor, with the estate roads having either 15 or 25 m buffers. The model was run with buffers for both distances, along all roads, catering for variation in the reach and ease of spreading; future iterations can allow for variations in reach distances and for full-block distribution. When spreader reach constraints are combined with the riparian exclusion zones, the pattern for biofertilizer distribution becomes complex. Combining trucking distance and within-field distribution allows allocation of management priorities and adjustment of field practices to maximize profitability.

Results: To illustrate the operation of the model, it was applied to a specific mill. There were no ground data from the mill, so the model was applied using remote sensing imagery (WorldView-3) and available regional data.

The *selection criteria* for the mill included the following: coverage by soil mapping at semi-detailed scale (1:63 360) or better; heterogeneous soils, so soil effects could be tested; and relatively cloud-free remote sensing imagery at moderate or high resolution. The selected mill, KKS Sungai Jernih, was located some 6 km from its nearest neighbour, with the estate backing onto a forested mountain to the west. In the absence of data on the estate boundaries, the model was applied to a circular zone of 3 km radius around the mill, encompassing all the visually apparent planted palm oil shown in the imagery used.

The soil map for the 3 km zone around KKS Sungai Jernih (Figure 8) derives from the WOSSAC copy of the semi-detailed (1:63 360) soil survey conducted during the *Pahang Tenggara Regional Study* (Huntings, 1971a). This map is at the coarsest feasible resolution; alternative reconnaissance-scale maps and regional or national overviews are considered too generalized for model use.

The suitability classes for biofertilizer incorporation and attendant benefits were assigned to the soil series (Figure 8a) according to the consensus on their suitability for the cultivation of palm oil, compiled from relevant report documents in WOSSAC (MSSS, 1977). The resultant suitability map (Figure 8b) shows the favouring of the deep, well-drained and fine-textured soil series, such as *Bungor*.

The low rating of deep loamy *Serdang* and the high ratings of shallow lateritic *Malacca* and imperfectly drained *Rusila* are surprising and will probably be modified in future model iterations. The high rating for Rusila is surprising and maybe because soil hydrology factors were not fully considered. Future applications will benefit from more recent and detailed soil maps, from soil hydrology studies, and from improved assessment of soil suitability for biofertilizers. Priority could be given to weakly structured sandy soils, as

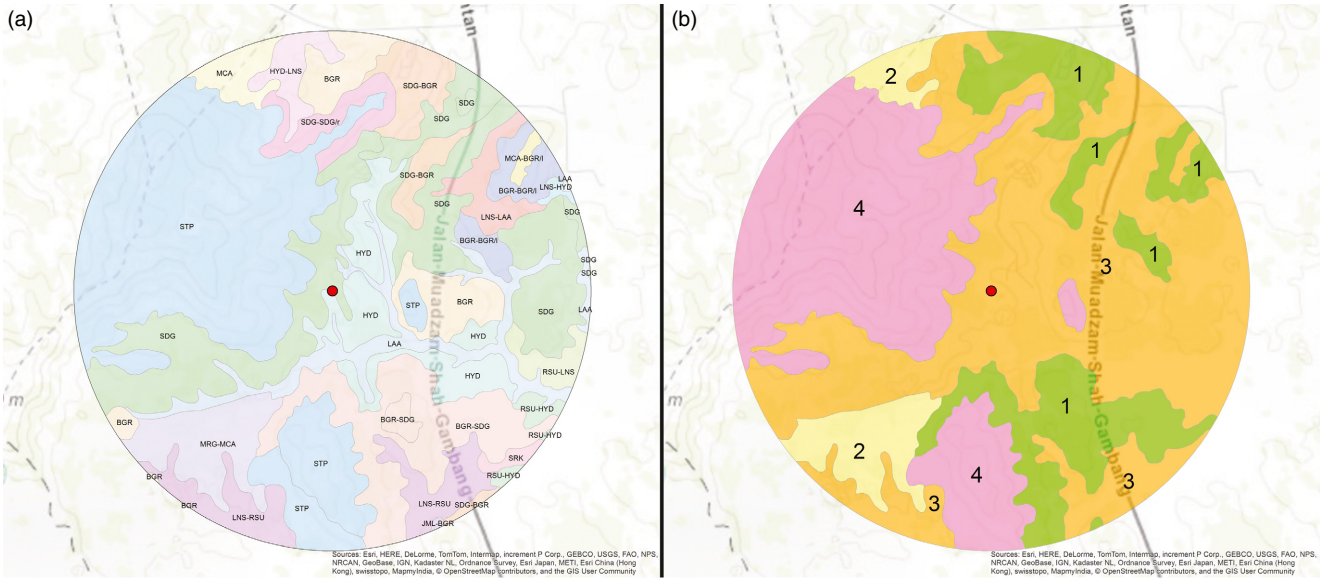


Figure 8 (a) Soil Series (1:63 360). (b) Preliminary land suitability for palm oil biofertilizer application around Sungai Jernih. Note: Red dot indicates the location of palm oil mill in Sungai Jernih. BGR, Bungor (deep clay); HYD, Holyrood (deep alluvial loam); LAA, Low active alluvium (imperfectly drained loam); LNS, Lunas (grey sandy); MCA, Malacca (loam with ironstone); MRG, Marang (terrace clay loam); RSU, Rusila (swampy); SDG, Serdang (deep loam); STP, Steep land (Huntings Technical Services, 1971b) | 1= Highly suitable (e.g. Bungor); 2 = Suitable (e.g. Malacca); 3 = Marginally suitable (e.g. Holyrood, LLA, Lunas, Marang, Rusila and Serdang); 4 = Unsuitable (e.g. Steep land).

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these are likely to physically benefit most from biofertilizer application, even if not offering the most profitable responses.

Discussion: The emphasis of this research is methodological, and the structure, assumptions and implications of the preliminary model are of more interest than the results of its application.

The present illustration is limited by the lack of replication and the lack of integration of the soil and transport and handling aspects. The assumptions about soil suitabilities, widths of riparian exclusion zones, trucking distances and roadside reach capacities are variable and influence results substantially. The ranking and distribution of zones will be greatly affected if sandy soils are given priority for compost. Assumptions will vary between mills, and the model will need to be adaptable to local conditions. However, this is the first time that available soil information in WOSSAC on Peninsular Malaysia has been digitized to produce a tool to assess land suitability to receive palm oil biofertilizer (Figure 8).

Further to this work, in considering the development of future iterations of the approach, it is intended the model could be deployed as an aid to mill and estate management, for the formulation of simple priorities and operational guidelines, rather than to prescribe distribution patterns in detail. Further model development will require specific collaboration with mills and Malaysian researchers. The problems encountered using only remotely available data will be avoided by such an approach. Detailed estate maps and working plans could provide comprehensive, specific assessment as to distribution, travel times, and trafficability of the roads, and distribution and size of streams and drains, and on current practices with respect to riparian exclusion zones. Many of the Malaysian soil materials in WOSSAC are dated, and the model would also be improved by access to contemporary soil data. The agronomic experience of each estate's management could therefore enable adjustments to the suitability of the local soils.

Integrated discussion for examples

Together, the examples highlight the role of LIS in supporting regional and national environmental challenges; LIS can play a key role supporting the development of strategic land management policies. The examples underline the extensibility of the methods and technical approaches employed in developing and applying LIS across different geographical contexts. The utility of the WOSSAC archive is demonstrated as a resource base for land capability modelling, a key strength of the approach being integration of its data with a variety of other complementary data sources. WOSSAC materials derive from many troubled parts of the world where, direct on-site access is currently restricted or in some cases considered dangerous. In this context, WOSSAC materials serve as a useful ground-truthing resource for contemporary sources of information, such as remote sensing. A second application for WOSSAC materials is provision of an environmental baseline, supporting longitudinal studies of environmental change, for example examining impacts of changing climate and consequent land degradation, or in understanding the spatial risks pertaining to soil protection (Kibblewhite *et al*., 2014).

Considering the examples against a range of themes (Table 2) reveals several points of convergence. As Figure 1 identifies, LIS are founded upon an environmental application, framed within a geographical context: land capability and suitability represent cross-cutting themes within the selected examples.

In some countries, access to cartographical data can present a challenge in the development of LIS approaches, both in access and usage. Although WOSSAC has been used to source appropriate mapping resources, the Malaysian example can be considered as a technology demonstrator, providing a basis and methodology for a future stage of development incorporating a review of intellectual property rights. Moreover, where data are hard to obtain, or where data are required at high density, the digital soil mapping approaches described in the Irish example can offer a potential solution.

As LIS implementations mature, so too do the mechanisms by which users can access the system outputs. The palm oil application, currently at an early developmental stage, had a specific and restricted audience – its results would be incorporated directly within estate plans for the managing palm oil by-products. Conversely, the Irish system provides a springboard for a broad range of future applications, which are to follow in the next stage of development, such as those in Table 1. An initial online resource (soils.teagasc.ie) provides public access to the uninterpreted Irish soil information. The LandIS implementation addresses a wide suite of access mechanisms, from direct data provision for expert users, to web-based reporting mechanisms (www.landis.org.uk), and via specialized 'Apps' developed for mobile devices, permitting the querying of localized, georeferenced data resources. A similar online information system exists for the extensive soil data in Scotland, including derived land capability other thematic maps of soil properties such as topsoil carbon (soils.environment.gov.scot). A pathway for future development has been identified for each of the examples considered (Table 2). Following the successful determination for Wales of a newly revised ALC, there is now scope to extend this approach to the English regions. Equally, where LandIS has a wide suite of applications drawing upon its soil resource information, there is scope to develop analogous applications in the Republic of Ireland, making full use of the new Irish soil resource base. Finally, where

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Table 2 Synthesis of Land Information System case studies

	LandIS: Agricultural Land Classification, Wales	National Land and Soil Information System, Ireland	WOSSAC: Land suitability for palm oil biofertilizers, Malaysia
Objectives	To undertake assessment of land suitability for agricultural use	To provide a new national soil resources base, replacing prior materials	To identify land suitability for receiving palm oil-derived biofertilizers
Methodologies	Custom iteration of Welsh soil association SMU membership, drawing on national expertise; integration of resultant resource materials within modelling framework	Combination of extensive field survey, with state-of-art digital soil assessment, geostatistical modelling and construction of enterprise-level information system/web public access tools	Custom capture & integration of specific resource materials, for example transport networks, introduced within modelling framework
Achievement	Successful revision of extant ALC modelling approaches, identifying contributory factors to grades and impact of future climate regimes on land assessments	Amongst the first national-scale digital soil assessments undertaken worldwide, integrating digital predictive mapping in a contemporary information system	A new, rational basis for planning application of palm oil by-products to land, based on a multicriteria assessment approach, minimizing environmental impacts
Access	Welsh Government seeks to make information available on websites such as the 'Environment Hub' www.werh.org for free public access and reference	Irish Government has made this information available as online resource soils.teagasc.i.e, for free public access and reference	Information to be integrated in estate management plans
Data constraints	Soil mapping at 'soil association' (grouped) level adds positional uncertainty when determining the land classification	Poor availability of existing soil data in some key soil landscapes has resulted in lower overall model performance	Poor availability of continuous soil mapping resources across all study locations; difficulties establishing data rights for access to key data
Development challenges	A larger scale is required for localized issues to be assessed. These maps are for strategic use only and are not for use in planning disputes	Developing a soil resource base maximizing future flexibility of usage. The many potential uses of the data are now under development	Development process necessitates capture of project-specific data (transport network) from satellite imagery in the estates
Outcomes	Support for agricultural policy; revised soil association membership in Wales	New national soil map & property database; revised soil association membership in Ireland; Baseline for soil function mapping and assessment	Basis for change in land management practices, founded on an evidence-based approach
Future development opportunities	To extend approach to English regions, drawing on newly proposed methodology	To develop a full range of thematic agronomic, environmental and engineering applications drawing on resource base	To extend approach to other palm oil mills, with targeted applications

SMU, Soil Mapping Unit.

examples of land suitability to receive oil palm by-products have been demonstrated for a limited number of the estates in peninsular Malaysia, so there is scope to extend this approach to the wider group of estates across the Peninsula and ultimately within mainland Malaysia.

The examples presented are constrained within the national boundaries of Wales, Ireland and Malaysia, respectively. However, where LIS applications extend across a land mass containing national boundaries, this presents issues with developing harmonized systems and derived applications (e.g. land capability). Often central to this are the different soil classification systems in use. For example, to produce UK-wide LIS, consideration is needed as to the harmonization of the two national soil classification systems used in Scotland, and in England and Wales. In England and Wales, a harmonized soil classification system (Hollis & Avery, 1997) permits ALC to be extended across these two countries. However, in Scotland, national assessments of land capability for agriculture are based on the Scottish national classification system (Lilly *et al*., 2015). Such issues are magnified when producing continental-scale soil information systems, such as the European Soil Database (Panagos, 2006) (esdac.jrc.ec.europa.eu/resource-type/european-soil-database-soil-properties) from national

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databases. In such cases, national soil classification schemes can be correlated to international soil classification systems [e.g. World Reference Base (IUSS, 2006)].

Conclusions

Land Information Systems provide a foundation for the provision of purposeful and timely environmental interpretations, drawing on soil and related thematic data, to offer insights into land properties, capabilities and characteristics, such as national ALC, the supporting of wider national environmental policies and assessment of suitability of land to receive palm oil biofertilizer.

The examples presented illustrate the development of national and regional applications in land information systems, revealing the practical transferability of technical and methodological approaches across geographical contexts. The examples demonstrate the value of natural resource inventories, used as a source of legacy information, which, once reconciled and integrated correctly, can be interoperated with other contemporary sources of information.

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Developments in land information systems: examples demonstrating land resource management capabilities and options

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