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Soil and transport factors in potential distribution systems for biofertilisers derived from palm oil mill residues in Malaysia

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ABSTRACT

Oil palm provides an important source of edible oils and fats, accounting for > 30% of total global production and > 55% of the international trade in these foodstuffs. The palms produce fresh fruit bunches, comprising several hundreds of small fruitlets, which are compressed and steamed to extract the oil. Soil nutrients in oil palm estates become depleted after decades of heavy harvesting and require fertilisers. Liquid palm oil mill effluent, solid empty fruit bunches and other residues can have deleterious environmental impacts and require careful management.

The problems of residue disposal and soil nutrient impoverishment can be linked and managed by composting the oil palm mill residues and distributing the biofertiliser produced back to the plantation. Using case studies from West Malaysia we present an early stage practical tool for the planning of the distribution component of such a cycle. The computer-based tool uses multiple field-based and remote sensing data sources to integrate the effects of local soil conditions, transport distances, environmental protection and management priorities and then models customised distribution plans. The tool operates at plantation level and can be augmented with detailed local data, but the approach is extensible and potentially applicable to regional or national planning.

1. Introduction

Oil palm (*Elaeis gunineensis*, Jacq.) is an important source of edible oils and fats, accounting for over 30% of total global production (European Palm Oil Alliance, 2016) and over 55% of the international trade in these foodstuffs. The oil palm tree produces large fruit bunches, each of which consist of several hundreds of small (50–100 g) fruitlets. The bulk of the oil is extracted from the fruitlet's fibrous mesocarp by compression and suffusion with superheated steam. Significant quantities are also derived from the endosperm. The species originated and was first cultivated in West Africa, which was the main source of palm oil before the Second World War. The semi-artisanal production there came from tall palms, the height of which complicated harvesting. Today, Southeast Asia is the main producer, and the crop has been transformed by decades of systematic breeding and development, particularly in Malaysia (Corley and Tinker, 2003). The stem has been dwarfed and crowns are now low enough to be harvested without climbing. Bunch yields and oil contents have also been increased many-fold. Mechanised harvesting is being explored to make the harvesting process quicker as detailed by Aljawadi et al. (2018) but there is also a need for considering safety, efficiency and ergonomic use with less labour force to fully implement this. Anyaoha et al. (2018a) report that upon harvesting empty fruit bunches (EFB), processing fruitlets causes minimal waste if it is undertaken through traditional approaches involving manual separation compared to industrial scale. Hence the recommendation is to integrate manual and industrial scale where fruitlets from the latter is passed on to the former to minimise waste generation.

Malaysia was the world's largest producer of palm oil for several decades but was overtaken by Indonesia in the early years of the 21st century. These two countries now account for more than 80% of global production and dominate the international trade (European Palm Oil Alliance, 2016). Most of the oil palm in Malaysia is grown on large, modern monocultural plantations, many of which are centred on a processing mill. In West (Peninsular) Malaysia, much of the oil palm was planted on former rubber plantations, which switched crops following the reduction in demand and increased production costs for natural rubber (Barlow, 1997). Most of the rest were planted *de novo* on converted forest lands. Some of the extensive plantations in the East Malaysian states of Sarawak and Sabah on Borneo were established on low but steep hills previously used for slash-and-burn shifting agriculture, including extensive degraded areas under the 'lalang' sword grass, *Imperata cylindrica* (Hansen, 2005; Wicke, 2011). Whilst there is a general negative connotation related to land conversion from virgin

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state to make way for oil palm plantations, Rochmyaningsih (2019) provides a green alternative by recommending an enhanced understory amongst the oil palms which mitigates nutrient loss, enriches the soil, minimises pesticide and herbicide use and promotes biodiversity.

Oil palm fruit bunches are bulky and weigh from 5 to 15 kg each in immature palms, averaging 23 to 27 kg in mature stands, occasionally reaching 50 kg (BCI, 1999). Yields are heavy, generating up to 30 tonnes fresh fruit bunches (FFB) ha^{-1} yr^{-1}. The bunches need to be transported to industrial-scale oil palm mills (OPM) for the extraction of the oil within 24 hours of harvesting, as delays in the processing degrade the quality of the oil. It takes 5–6 tonnes FFB to produce one tonne of oil, and Malaysia's current annual production of about 20 million tonnes of oil (Malaysian Palm Oil Board, 2018) generates about 100 million tonnes of residues. The most important of these are liquid palm oil mill effluent (POME) and solid empty fruit bunches (EFB), but there are also substantial quantities of sludge, shells and press cake (Hassan et al., 2005; Agamuthu, 2009; Shuit et al., 2009; Griffin et al., 2014). One tonne of FFB generates 0.5–0.75 tonnes POME (Rupani et al., 2010), a dark, oily and acid liquid with high biological and chemical oxygen demands. These properties, and particularly the contents of oil and grease, preclude the release of POME into drainage systems, and this has been proscribed for decades (DOE, 1974, 1994; Government of Malaysia, 1977, 1979). Much POME is retained in ponds adjacent to mills. These occupy valuable space and release noxious gases and odour. One tonne of ponded POME can emit *ca.* 33 kg methane, which is the greenhouse gas equivalent of *ca* 750 kg CO_2 (Rupani et al., 2010). EFB are less of a chemical problem, but their bulk presents considerable storage and disposal problems, and their dumps often occupy several hectares of potentially useful land adjacent to the mills.

Consequently, there is an increasing interest in the oil palm industry, in Malaysia and elsewhere, in exploiting the potential of these materials as resources rather than disposal problems. Possible uses include: bio-energy generation by combustion or fermentation; supplementary feedstock in the production of fodder for livestock and fishponds; and raw materials for the pharmaceutical and chemical industries (Ahmad, 2015). They also have potential as fertiliser feedstock for conversion by pyrolysis, gasification, combustion or composting to products such as biochar, ash or compost to benefit soil and crops (Anyaoha et al., 2018b).

There are parallel interests in the resource potentials of the processing by-products from other tropical plantation crops. Coffee silverskins and spent coffee grounds, the main residues of the processing of coffee beans, have potential as feedstocks for biochemical production of saccharides, glycerides and alkanes, and also for the production of biochar (Mussatto et al., 2011). Cacao husks also show potential for the production of activated carbon for adsorbents and filters (Cruz et al., 2012). The processing residues from these crops are of higher biochemical value but much lower volumes than OPM waste.

Agamuthu (2009), Kala et al. (2009), Mohammed et al. (2011) and Vakili et al. (2015) provide overviews of the potential of OPM residues for composting, and also note other potential uses such as feedstocks for biofuel, ethanol, organic acids, bioplastics and other chemicals. Composting OPM residues produces large volumes of biofertilisers at or near the mill, and can be used in the adjacent plantation which minimises transport costs. Appropriate application of the biofertiliser can improve soil water retention, reduce soil erosion, reduce inorganic fertiliser requirements, and increase yields. The data of Ahmad (2015) indicate that composted POME/EFB biofertiliser applied at 100 t/ha contains about 65 kg N, 10 kg P, 145kg K and 70 kg Mg, with variations due to moisture content, and volatilisation and leaching losses. These nutrients could substitute for commercial fertilisers at about 140 kg/ha urea, 65 kg/ha Christmas Island Rock Phosphate, 280 kg/ha muriate of potash, and 100 kg/ha kieserite. However, the chemical effects of biofertiliser extend beyond nutrient supplementation, and the soil organic matter (SOM) will be enhanced and may have significantly higher ratios of humic to fulvic acids, higher aromaticity, and higher density of active groups (Rivero et al., 2004). With experimentation and accumulated field experience, composting can be adjusted to generate different products. When banana stems are composted with chicken manure, N losses by volatilisation are increased by the addition of rice straw but decreased with bagasse (Wu et al., 2011).

Composting is environmentally preferable to bio-energy production as it facilitates substantial carbon sequestration, with most of the carbon in the residues eventually being incorporated within the SOM, rather than being emitted to the atmosphere as CO_2. However, composting is not emission-free, as the increases in soil faunal and microbial activities generate CO_2, methane and other greenhouse gases. Nonetheless, composting emits only ca 10–15% CO_2 equivalents compared with combustion for energy (Aye and Widjaya, 2006; Rahman et al., 2019).

Whilst the composting techniques for OPM residues and the benefits to soil and crops have been widely documented, there has been less work on the practicalities and logistics of biofertiliser handling in oil palm plantations. We here aim to report on the early stage of a decision support tool to optimise the application of OPM biofertiliser. Using geospatial information we used the tool to model the effects of land quality, transport distances, and environmental protection on the distribution and application of OPM biofertiliser in four Malaysian oil palm plantations. When translated into routine practice, the tool will assist closure of the loop in a local carbon and nutrient circular economy.

2. Materials and methods

2.1. Approach

The effects of external factors on potential distribution systems for OPM biofertilisers in Malaysian plantations are integrated from soil attributes and suitabilities for oil palm cultivation, transport distances, and environmental protection measures. The geo-referenced Geographical Information Systems (GIS) data layers for soils, roads and streams are overlaid and the resultant patterns are assessed.

The relative importance of the factors varies between plantations, according to the local circumstances and management priorities, and the procedure can accommodate this. It also allows for intra-plantation adjustment where local environments are heterogeneous. It is intended to be applied at the level of individual plantations. It can contribute to regional or national guidelines, but only if similar combinations of conditions apply to multiple plantations.

We allow for two contrasting soil management scenarios. In Scenario 1 the biofertiliser is applied on the most fertile soils, where the incremental return of yield per unit fertiliser is likely to be high. In Scenario 2 the biofertiliser is applied to less fertile but well-drained sandy soils, some of which are known as *bris* in West Malaysia (Paramanathan, 2015). This is likely to generate greater soil improvements, lower erodibility, and possibly greater carbon sequestration. Although it may achieve lower yield increases, it could smooth out intra-plantation yield differences.

2.2. Study sites

The tool was used for both strategies and applied to plantations around four mills (Table 1). They were selected because there were sufficient data to generate the necessary GIS data layers (Table 2). The soils of the four plantations have been mapped at a semi-detailed scale or finer, and the surveys are available in the World Soil Survey Archive and Catalogue (WOSSAC) at Cranfield University (Hallett et al., 2017, 2011). They indicate variable levels of soil heterogeneity. Relatively cloud-free, remotely sensed imagery (Digital Globe WorldView-3 imagery) was available at moderate or high resolutions, which enabled digitisation of the road and stream networks. Two of the plantations are located in central Pahang and the other two in central Johor (Fig. 1).

Table 1
Malaysian oil palm plantation study sites.

Number on Fig. 1 (Catalogue number, SIRIM, 2015)	Plantation	State	Latitude (DD)	Longitude (DD)
102	Kilang Kelapa Sawit **Bukit Leelau**	Pahang	3.30 N	103.14 E
150	Kilang Kelapa Sawit **Sungai Jernih**	Pahang	3.34 N	103.10 E
11	Kilang Kelapa Sawit **Simpang Wa Ha**	Johor	1.79 N	104.07 E
19	Kilang Kelapa Sawit **Lok Heng**	Johor	1.72 N	104.12 E

Pahang and Johor are the states in Peninsular Malaysia with largest areas of oil palm plantations, with each accounting for 13% of the national total (Malaysian Palm Oil Board, 2017).

2.3. Layer generation

2.3.1. Streams

Malaysia has stringent regulations for the protection of the natural environment, including water resources. Release of proscribed material, such as POME, into surface- and ground-waters is forbidden, as are a number of potentially harmful activities near stream banks (DOE, 1974, 1994; Government of Malaysia, 1977, 1979). OPM biofertilisers are less harmful than raw POME, but have some potential to degrade water quality. The spreading of biofertilisers near streams is not explicitly proscribed at present, but this could change in the future as the quantities and use increase. Our procedure therefore excludes biofertiliser spreading within riparian protection zones. Riparian zone width can be varied, but a default of 15 m either side of the stream centreline was adopted as an initial standard. Zonation was applied to artificial drains as well as streams, as these eventually feed into the natural drainage systems. The 15 m zonation is applied throughout all four study sites. However, the by-products of biofertiliser decomposition can more readily infiltrate and drain through coarse textured soils or stratified alluvial soils, and thus increase the risk of water pollution. We therefore varied zone width according to the texture of the stream bank soils in a sample area at the Sungai Jernih study site (Fig. 3).

The stream network was derived from a combination of hydrological analysis of a Digital Elevation Model (DEM) and visual interpretation from remotely sensed imagery. Initially a stream network was generated automatically using the hydrological tools in ESRI ArcGIS (ESRI, 2018). This process used the 3 arc second (approximately 90 m) resolution Shuttle Radar Topography Mission (SRTM) DEM, to extract a stream network based purely on topography. The location of the streams features were then refined visually using remotely sensed images at a range of dates (Table 2). These images also included stream/ditch features that are man-made and therefore not generated in the initial automated hydrological analysis. The stream/ditch networks were then buffered by a standard width of 15 m either side of the stream centre line for average soils. The width was varied according to the permeability of the riparian soils for part of the Sungai Jernih study site. This was increased to 25 m for sandy soils and decreased to 10 m for fine-textured and imperfectly drained soils with low permeability. Each soil type is assigned to a permeability and zone width class in Table 3.

2.3.2. Plantation roads

Because FFB yields may reach 30 tonnes/ha, modern oil palm presents substantial harvesting problems, with large volumes of material needing to be transported rapidly to the mill. Modern oil palm plantations therefore have dense networks of internal roads (Morris, 1970; Malaysian Palm Oil Board, 2010). Although initially constructed for harvesting, these roads can be used to distribute biofertilisers. Because the bulk, weight, distance and gradient represent major determinants of transport costs, especially in the steep hilly terrain of the plantations in East Malaysia. These are subdivided into two major components – road distance and gradient from the composting facility to the edge of the block, and the within-block distance from the roadside.

Road distances to block edge would be best quantified as 'drive times'. However, data permitting this calculation is not currently available, so road distances from the composting facility to block edge were adopted as a surrogate. GIS layers for the road networks were generated from visual interpretation of remotely sensed imagery. Road centre lines were digitised for all major and minor plantation roads from remotely sensed images at a range of dates (Table 2). Imagery from multiple time periods allowed significant coverage of the whole plantation and reduced masking by clouds. Travel distances from the

Table 2
Key spatial themes.

Layer	Data source	Coordinate system	Processing
Mill location	SIRIM, 2015	GCS WGS 1984	Plot locations
	ESRI World imagery layer, ArcGIS map service		
Stream vector line	Digital Globe WorldView-3, 31 cm panchromatic, 1.24 m multispectral resolution	GCS WGS 1984	Interpretation and digitising
	ESRI World imagery layer, ArcGIS map service	GCS WGS 1984	Interpretation and digitising
	SRTM DEM, 3 arc second resolution	GCS WGS 1984	Hydrological analysis
Road vector line	Digital Globe WorldView-3, 31 cm panchromatic, 1.24 m multispectral resolution	GCS WGS 1984	Interpretation and digitising
	ESRI World imagery layer, ArcGIS map service	GCS WGS 1984	Interpretation and digitising
	Landsat 8, 15 m panchromatic, 30 m multispectral resolution	WGS 1984 UTM Zone 48N	Interpretation and digitising
Soil vector polygon	WOSSAC soil maps: ID 24087, *Pahang Tenggara Soil Survey*, 1:63,360 scale, Foundation of Canada Engineering Corporation, 1972* ID 24147, *Johor Tenggara Soil Survey*, 1:63,360 scale, Hunting Technical Services, 1971a**	WGS 1984 UTM Zone 48N	Digitisation
Fertiliser suitability vector polygon	Soil layer, fertiliser suitability lookup table	WGS 1984 UTM Zone 48N	Linking to the soils data to allow lookup of suitability

* https://www.wossac.com/search/wossac_detail.cfm?ID = 24087.
** https://www.wossac.com/search/wossac_detail.cfm?ID = 24147.

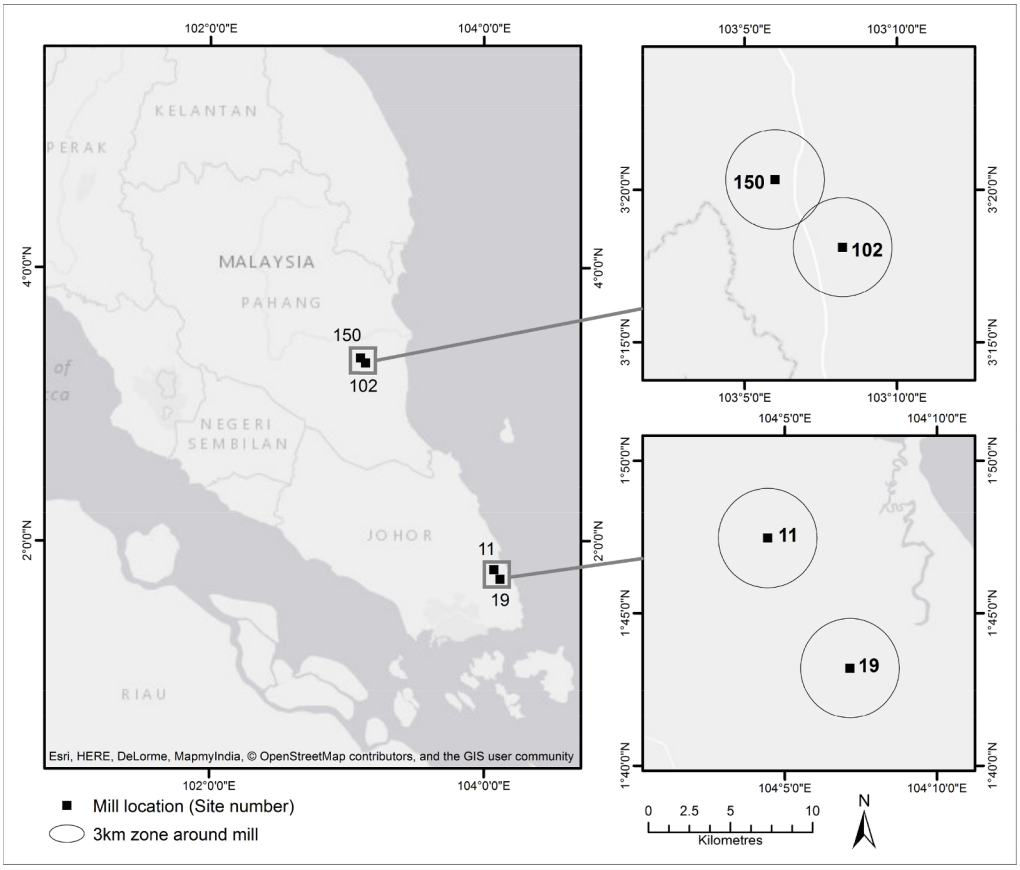


Fig. 1. Location of study sites in Peninsular Malaysia. Mill numbers are from SIRIM (2015).

Table 3
Soil series and land units in study areas.

Soil	Code	Main features	Suitability for OPM biofertiliser*		*Riparaian zone width (m)*
			Scenario 1	Scenario 2	
Soil Series					
Bungor	BGR	Deep, well drained brown fine loam on sandy shale	1	3	10
Durian	DRN	Moderately deep, well drained brown fine loam on shale	2	3	10
Holyrood	HYD	Deep, moderately drained grey-yellow coarse loam on older alluvium	3	1	25
Jempol	JML	Deep, well drained reddish fine loam on tuffaceous shale	1	3	10
Jerangau	JRA	Deep, well drained reddish yellow fine loam on granodiorite	1	3	10
Lunas	LNS	Deep poorly drained grey coarse loam on older alluvium	3	3	25
Malacca	MCA	Shallow, well drained, brown fine loam–clay over ferricrete	2	3	10
Marang	MGR	Moderately deep, well drained, pale loam on sandy shale & quartzite	2	3	25
Rengam	RGM	Deep, well drained brown fine loam on granite	2	2	10
Rasau	RSU	Deep imperfectly drained grey sand on older alluvium	3	2	25
Serdang	SDG	Deep, well drained, reddish yellow loam on sandstone & quartzite	3	2	25
Serok	SRK	Deep, well drained, yellow loam on older alluvium	2	3	25
Tavy	TVY	Moderately deep and drained yellowish fine loam over ferricrete	3	3	10
Land Unit					
Alluvial complex	ALC	Deep poorly – moderately drained grey mixed textures on recent alluvium (similar to LAA)	3	3	25
Local alluvium	LAA	Deep poorly – moderately drained grey mixed textures on recent alluvium (similar to ALC)	3	3	25
Organic clay	OCM	Wet muck and clay in swamps & depressions	4	4	25
Peat	PET	Black drainable peat, variable depth	2	2	25
Steepland	STP	Slopes too steep for oil palm cultivation and harvesting	4	4	25

* Suitability 1 = high through to 4 = unsuitable. From: Corley and Tinker (2003); Hunting Technical Services (1971b); Hunting Technical Services and Tippetts-Abbett-McCarthy-Stratton (1967).

mill composting facility were calculated from an ArcGIS road network dataset, which produced a service area layer with defined break values established at 1, 2, 3 and 4 km.

Manual handling materials from the roadside for application within blocks is expensive. At present, there is within-block access for tractor-mounted loaders and trailers for harvesting in some plantations. Tractor spreading of solid biofertilisers is therefore feasible in some areas. Other mechanised distribution systems, such as pumps, blowers or elevators, may be necessary and feasible, depending on the nature of the biofertiliser (liquid, slurry, or moist solid) and the local topography.

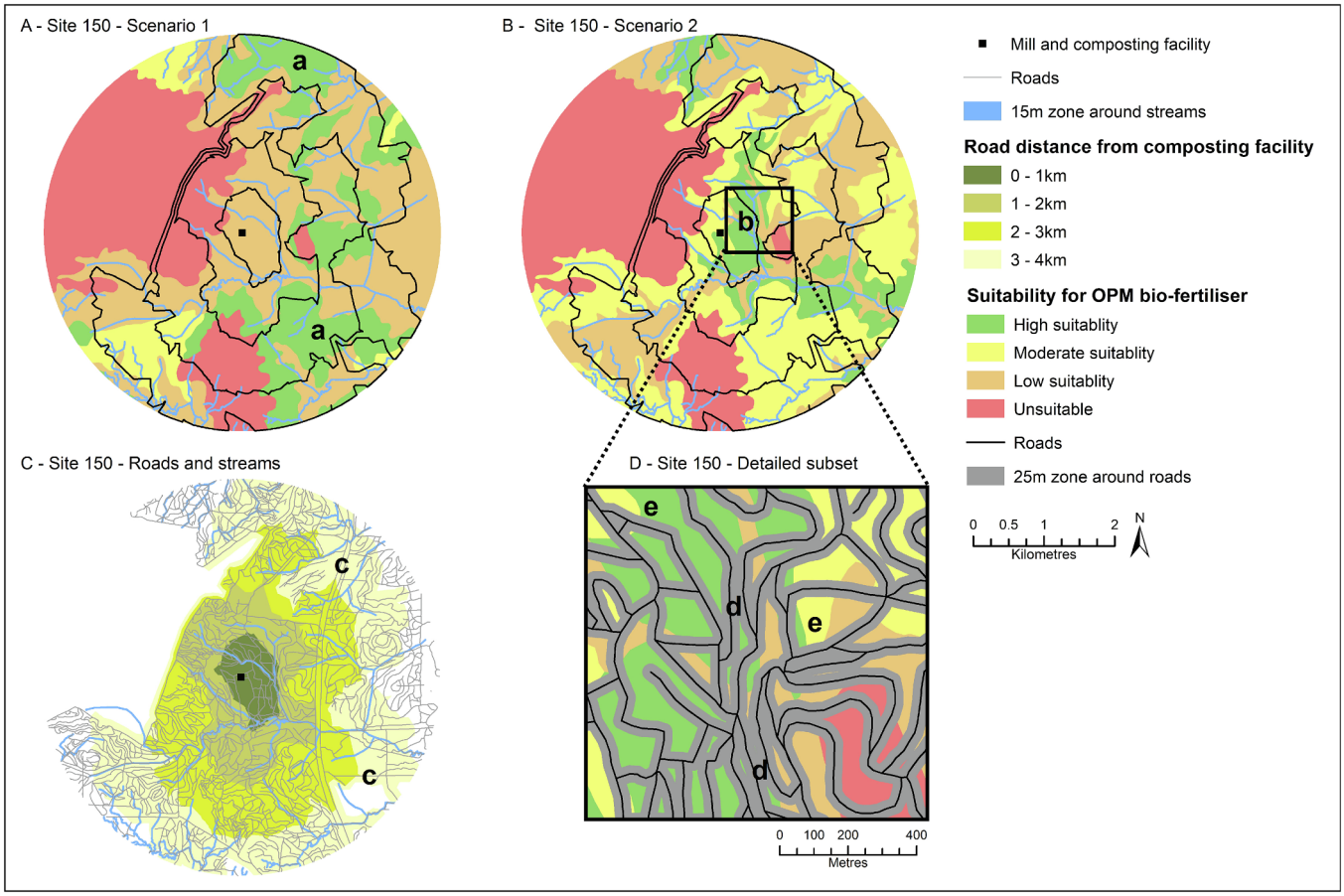


Fig. 2. Application of tool to KKP 150 Sungai Jernih, Pahang. (A) and (B) Land suitability for biofertiliser application in Scenarios 1 and 2. (C) Roads, road travel distance zones, streams, streambank 15 m buffer zones. (D) Zoom-in detail with 25 m roadside zones.

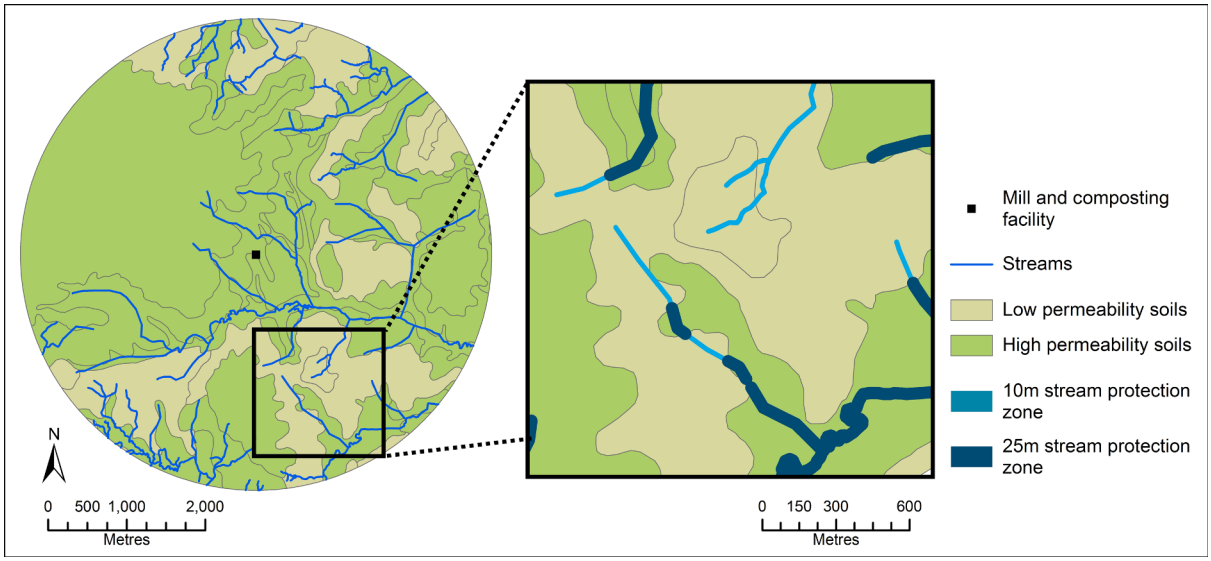


Fig. 3. Soil permeability zones at Sungai Jernih.

It was assumed that within-block spreading costs will increase substantially at distances greater than about 25 m from roadside, so the road networks were buffered initially to 25 m either side of the centreline.

2.3.3. Soils and biofertiliser suitability

The effect of soils on the distribution of OPM biofertiliser are derived from two overlapping and interacting sets of soil attributes and processes. The first relates to the capacity of the soil ecosystem to physically incorporate large but episodic imports of surface-applied

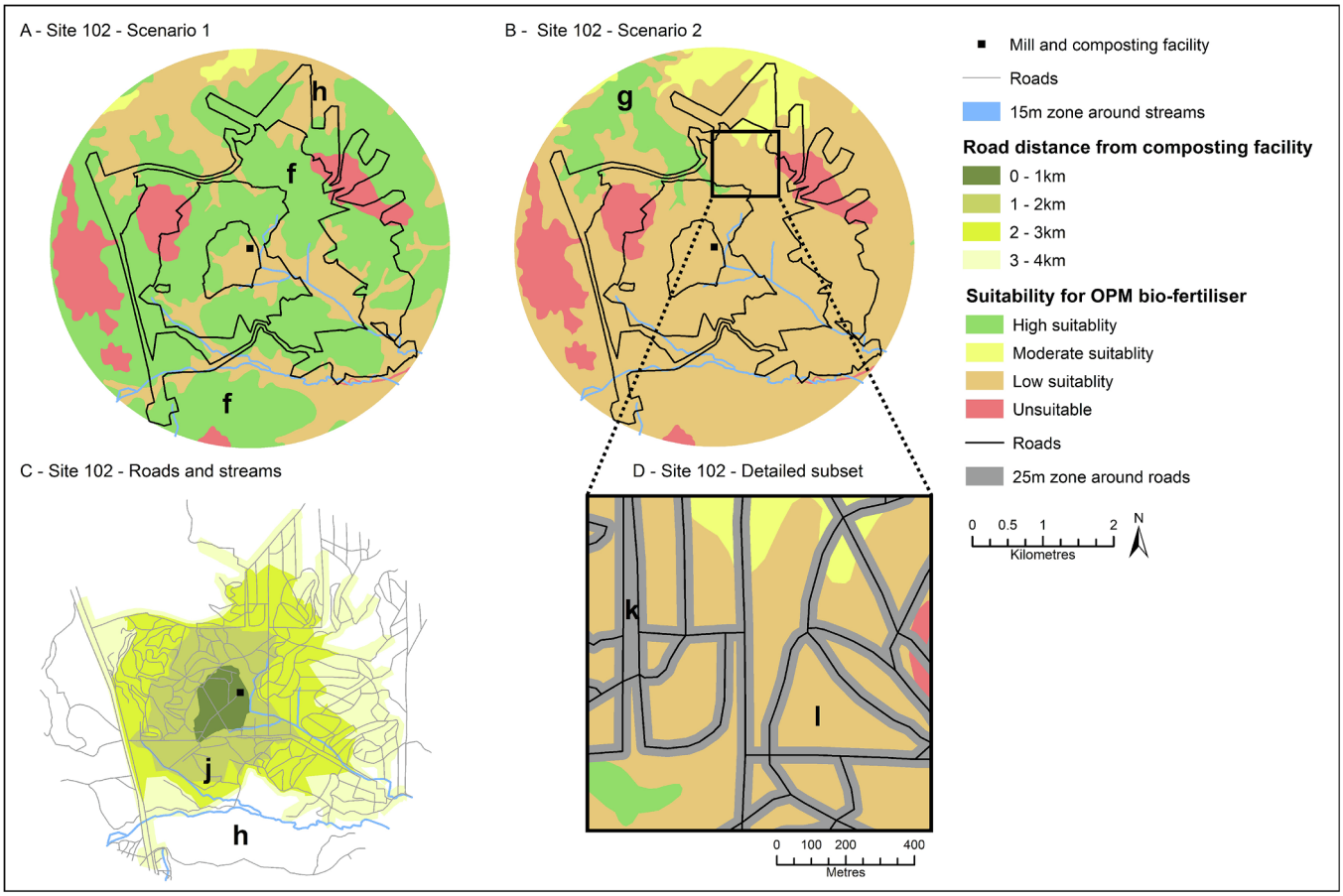


Fig. 4. Application of tool to KKP 102 Bukit Leelau, Pahang. (A) and (B) Land suitability for biofertiliser application in Scenarios 1 and 2. (C) Roads, road travel distance zones, streams, streambank 15 m buffer zones. (D) Zoom-in detail with 25 m roadside zones.

organic materials. Rapid incorporation into the mineral profile of the soil reduces the risk that the fertiliser will be washed from the soil surface and transported into the local drainage network during intense rainfall. Incorporation is primarily effected by the burrowing, food burial and other pedo-turbation activities of large, diverse and vigorous populations of soil macrofauna, especially earthworms, ants and termites. Once in the soil, the second process involves the chemical processing of the incorporated biofertiliser by soil microbes, which decompose the residues and mobilise many of the nutrients to forms that are eventually available for crop uptake. The metabolic activities of the soil biota utilise some of the energy content of the biofertiliser, generating CO_2 within the soil pore system, which diffuses out to the atmosphere.

For the 'best soils' Scenario 1 it was assumed that the greatest marginal benefits will accrue on the best oil palm soils, and we rate the soil series of the study areas according to their suitability for oil palm (Corley and Tinker, 2003; Hunting Technical Services and Tippetts-Abbett-McCarthy-Stratton, 1967). For the 'soil improvement' Scenario 2, higher ratings were assigned to less fertile, but well drained sandy and coarse loamy soil series (Chan, 1977). All of the soil series and associations that were mapped in the four study sites were rated using criteria appropriate to these two scenarios (Table 3).

The spatial distributions of the soils for the plantations were digitised from the WOSSAC soil maps (Hallett et al., 2017). A polygon layer with map unit attributes was created. The soil map units were combined with a lookup table containing 'Suitability for OPM biofertiliser' for Scenarios 1 and 2 (Table 3).

3. Results

Application of the tool to the plantation number 150 (Table 1) at Sungai Jernih (Fig. 2) shows: streams and land suitabilities for biofertiliser allocation, according to the two soil management scenarios (Fig. 2(A and B)); 1, 2, 3 and 4 km travel distance zones along the plantation roads out from mill/composting facility; and streams and their buffer zones (Fig. 2C); and details of the Scenario 2 suitability zones, roads and 25 m roadside distribution zones in a sample area to the northwest of the mill (Fig. 2D).

Sungai Jernih has heterogeneous soils, and Fig. 2A shows that there are few areas of high or moderate suitability for Scenario 1 within the 1 km road distance from the mill. The best land is mostly located 2 – 3 km from the mill (e.g. a in Fig. 2A). For Scenario 2 there are considerable areas of medium textured and moderately well drained alluvial soils to the west of the mill that are assessed as suitable. There are similar areas along the main stream to the northeast that are within 2 km by road from the mill (e.g. b in Fig. 2B).

Area c in Fig. 2C shows low road densities in an area of mature oil palms. The overlapping crowns obscure all but very short stretches of roads, which cannot therefore be interpreted as a continuous network. Roads in the obscured areas are assumed to be actually similar in density and pattern to the rest of the plantation. The generally high road density means that some blocks are less than 50 m wide and contain no land more than 25 m from a roadside (e.g. d in Fig. 2D). However, the topographic configuration can also necessitate wider blocks, the centres of which are up to 80 m from roadside, and these will incur higher distribution costs (e.g. e in Fig. 2D).

To allow for the risk of seepage of biofertilisers and their

decomposition products into the drainage system, we delineated variable width riparian protection zones to a test area at Sungai Jernih according to the soil type of the stream banks (Fig. 3).

The soil pattern of plantation Kilang Kelapa (KKP) 102 at Bukit Leelau is also heterogeneous (Fig. 4(A and B)) and results in a clear contrast between the two scenarios. There are extensive tracts of moderately drained, fine textured soils which grade as highly suitable for Scenario 1, but downgrade to low suitability in Scenario 2 (e.g. f on Fig. 4A). There are areas of coarser textured soils that are upgraded in Scenario 2 (e.g. g on Fig. 4B) but these are less extensive. As at Sungai Jernih, areas of apparently low road densities are artefacts caused by dense overlapping crowns of mature oil palm (h on Fig. 4C) and also some cloud cover (j). The detailed subset shows blocks with easy access from roadside (e.g. k on Fig. 4D) and those with areas significantly further from a road (l).

The soils of KKP 11 at Simpang Wa Ha are relatively homogeneous and unlikely to be a major influence on biofertiliser distribution. The bulk of the plantation is of moderate suitability under both scenarios, with only limited areas of downgrade (e.g. m on Fig. 5A) and upgrade (n) from Scenario 1 to 2. The apparently low road densities are again due to overlapping oil palm crowns (p on Fig. 5C), but there is also significant cloud cover (q).

The Lok Heng plantation KKP 19 is intermediate, with large areas of land that is moderately suitable for Scenario 1 around the mill (e.g. r on Fig. 6A). Much of this land is downgraded to low suitability in Scenario 2 (e.g. s on Fig. 6B). Road densities are high in some areas designated as unsuitable, suggesting that this plantation uses some imperfectly drained alluvial soils (e.g. t on Fig. 6D) and shallow soils on moderate slopes (e.g. u on Fig. 6D).

4. Discussion

The four plantations for this study were selected because the soils data held in WOSSAC (Hallett et al., 2017) indicated a variety of soil patterns and also because we had access to appropriate localised and high-resolution remote sensing imagery. The tool is pragmatic and uncomplicated, being based on soils, roads and streams. It identifies various options for the spatial distribution of biofertiliser in oil palm plantations in Malaysia, and is flexible enough to accommodate different soil management strategies.

The tool would be improved if it were moved from desk to plantation. Collaboration with plantation managements could provide access to more detailed and recent mapping. Local interpretation of the soils pattern would improve biofertiliser suitability ratings and zonation. Detailed ground-surveyed maps of the plantation roads would enable refinement of the travel criteria, thereby permitting substitution of actual travel times for road distance. Combined with detailed topographic mapping and identification of steep grades, road times could be further transformed into travel costs. The zonation of within-field spreading could also be refined in line with local technical preferences, available equipment and capacities.

Detailed maps of the streams and drains would enable more flexible zonation of riparian protection zones. Zone widths could be adjusted locally, with individual plantations setting their own limits until biofertiliser spreading is nationally regulated. As noted in in Fig. 3, zone width could be adjusted for soil type (Table 3).

The tool could be refined by the incorporation of additional criteria. These might include allowances for variability in the pre-processing and types of biofertiliser. Those with high nutrient concentrations would incur lower transport cost per unit of fertility, and might be used

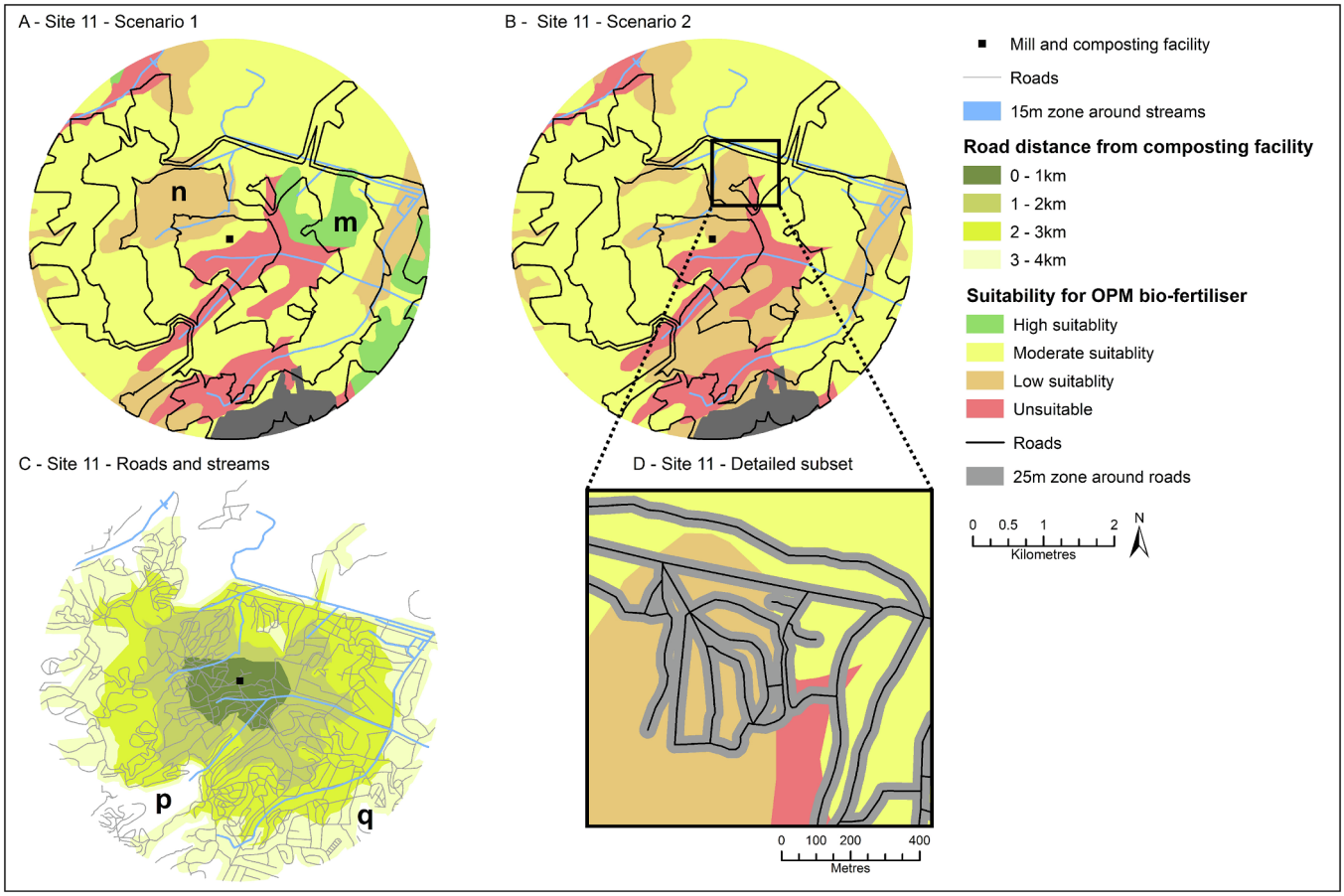


Fig. 5. Application of tool to KKP 11 Simpang Wa Ha, Johor. (A) and (B) Land suitability for biofertiliser application in Scenarios 1 and 2. (C) Roads, road travel distance zones, streams, streambank 15 m buffer zones. (D) Zoom-in detail with 25 m roadside zones.

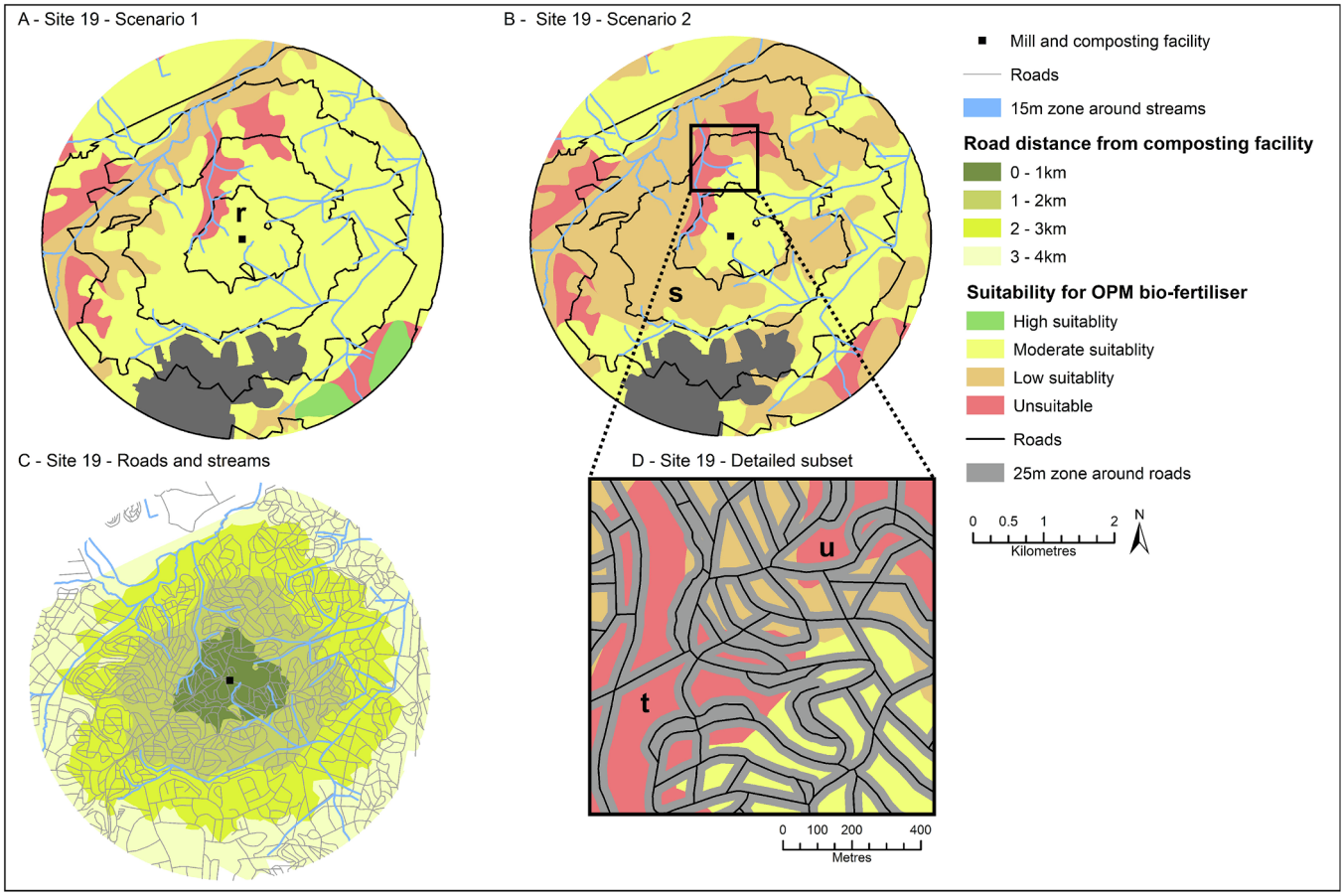


Fig. 6. Application of tool to KKP 19 Lok Heng, Johor. (A) and (B) Land suitability for biofertiliser application in Scenarios 1 and 2. (C) Roads, road travel distance zones, streams, streambank 15 m buffer zones. (D) Zoom-in detail with 25 m roadside zones.

for more distant blocks. Bulkier and less concentrated, but still worthwhile biofertilisers, could be used in areas close to the mill. Road quality and capacity might also be included in the travel criteria. Other criteria that could be added include age of the palm and varieties or clones of palm used in plantations and how that matches fertiliser requirements.

Biofertiliser application cannot be considered in isolation, and their production and distribution should be integrated with other aspects of management. The application of biofertiliser may modify the management of residual palm litter that does not get exported to the mill. At present the cut palm fronds are often laid in the tractor paths between rows to reduce soil compaction. Other litter, including male inflorescences and abscised frond bases, are often mulched around the palms. When the palms are felled, at 20–30 years, the trunks and those frond bases still-attached are left to rot *in situ* in some plantations. However, there is increasing investigation on the uses of oil palm trunks as a source of sugars, starches and fibre, and they may in future be removed for processing. The export of trunks might reduce inter-generational infection of basal stem roots in new plantings (Flood et al., 2005). However, it will intensify depletion of the site's nutrient stocks.

Since the main ingredients are EFB and POME, there is little scope for siting composting facilities anywhere except adjacent to their mill. In established plantations, the roads were laid out primarily for harvesting. However, the design of road systems in areas of pioneer plantings might benefit from GIS analyses using bulk material transportation models and algorithms (Cheng & Chang, 2002). There is also some potential for local pragmatic adjustments. For instance, a plantation might opt to apply the biofertiliser on all blocks close to the mill in order to minimise transport costs, irrespective of soil suitability, but apply soil suitability criteria for more distant blocks.

5. Conclusions

Malaysia has extensive modern oil palm plantations and many processing mills. The mills generates large volumes of residues, principally liquid palm oil mill effluent and solid empty fruit bunches. These can impact negatively on the environment. Decades of high yields substantially deplete oil palm soils of nutrients. Composting of the residues and their distribution as biofertiliser can serve to address both of these issues by creating a local circular economy.

We concentrate on the distribution segment and present an early stage tool that can guide decision-making in the transport of OPM biofertilisers. Our tool integrates the effects of soil patterns, transport distances, and environmental protection on the practicalities of the distribution and application. It is designed for application at plantation level, and can be improved by the incorporation of detailed localised knowledge. The tool can be useful in plantation environmental management planning. Furthermore, the tool can be developed to assist planning and assess impacts at regional and national scales.

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Declaration of Competing Interest

None.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2019.105005.

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Soil and transport factors in potential distribution systems for biofertilisers derived from palm oil mill residues in Malaysia

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